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FINAL REPORT

for

THRUST AUGMENTATION SYSTEM FOR LOW-COST-EXPENDABLE TURBOJET ENGINE

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During the performance period, a dump-combustor afterburner and water/methanol injection system were designed, fabricated and tested on a Sundstrand TJ-90 expendable-turbojet engine. Maximum thrust measured was 150 lbs. yielding an augmentation ratio of 1.57. Also evaluated were silicone based and alumina based lining materials for the afterburner combustion tube and coated-graphite and alumina based materials for the exit nozzle. Water/methanol injection was tested at four engine stations: 8 inches upstream of the compressor face, directly upstream of the compressor deswirl vanes, directly into the combustor dilution region and downstream of the turbine exit. Maximum predicted water/methanol flow rates could not be achieved due to combustor flame out. Performance was measured dry, with water/methanol only, with afterburner only and with afterburner and water/methanol injection.

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FINAL REPORT

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THRUST AUGMENTATION SYSTEM FOR LOW-COST-EXPENDABLE TURBOJET ENGINE

CONTRACT NO. DAAH01-92-C-R359

CONTRACT PERIOD: June 26, 1992 to March 31, 1993

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EXECUTIVE SUMMARY

Employment of an augmented turbojet propulsion system, capable of high thrust for initial boost and efficient-reduced thrust for sustainer operation, will eliminate the need for the solid-rocket booster normally required to launch a turbojet-powered tactical missile. The separate turbojet and solid-fuel rocket systems would thus be replaced with a single integrated system. An additional advantage of this type of system is the ability to turn the augmenter on and off, at will, throughout the mission.

For this program, M-DOT conducted basic research into cycle characteristics of the Sundstrand TJ-90 Turbojet Engine and designed, fabricated and tested a thrust-augmentation system which increased measured static thrust 57% from 95 lbs at 100K rpm to 150 lbs at 100K rpm. Augmentation was achieved through exhaust reheat (afterburning) and water/methanol injection upstream and downstream of the engine compressor.

Main components of the system were:

- O **Ablative-lined dump-combustor afterburner**. This consisted of diffuser, flame tube with step-flame holder, ignitor, fuel injectors, fuel manifold and coated-graphite or masonry exhaust nozzle.

- O **Engine inlet water/methanol injection system**. This consisted of fiberglass-inlet section with centerbody, three centrifugal-atomizing spray nozzles, manifold and electric pump.

- O **Post-compressor water/methanol injection system**. Two configurations were tested. One consisted of a copper manifold with 12 stainless-steel injector tubes that introduced fluid directly into the combustor. The other configuration consisted of an aluminum annulus pressed directly onto the compressor housing. From this annulus, fluid was introduced into the flow path in front of the compressor-deswirl vanes through 12 ports.

Hardware was designed and fabricated at M-DOT. Research papers on fabrication and testing of dump-combustor afterburners from AiResearch and the Air Force Institute of Technology provided a basis for the afterburner design. Basic thermodynamic calculations and knowledge of shearing flow and atomization were used to configure the water/methanol injection system. Initial calculations indicated that a thrust augmentation ratio of 2.0 could be achieved on the TJ-90 engine at an exhaust-reheat temperature of 3200° F and a water/methanol flow rate of 15.0 lbm. per minute. Hot section and afterburner hardware was fabricated from type 347 stainless steel and Haynes 188 sheet stock with machined bosses and flanges where required for fuel inlets and instrumentation. Inlet ducting and fairings were made from glass-reinforced epoxy with aluminum inserts for flanges. For initial performance testing, a water-cooled afterburner was fabricated. After this unit failed during testing, ablative and refractory liners were employed to prevent melting of the afterburner structure.

The test engine was a prototype TJ-90 turbojet manufactured by Sundstrand Turbomach of San Diego CA and loaned to M-DOT by the Army for this program. Modifications were made to

the engine at M-DOT to incorporate water/methanol injection manifolds, remove the fuel pump and reconfigure the start-air delivery tubes. A thrust-calibration nozzle and exhaust-instrumentation duct were supplied with the engine.

Testing was conducted on an M-DOT-owned calibrated thrust stand. Instrumentation consisted of type K (chromel-alumel) thermocouples at all engine stations except the afterburner exit, type B (platinum-rhodium) thermocouples at the afterburner exit, static pressure taps throughout the flow path, engine-shaft speed, bearing temperature, fuel flow rate, water/methanol flow rate and thrust. Fuel was Jet-A aviation kerosene. Prior to testing the augmenter, the engine was baselined using the supplied calibration nozzle. Measured thrust at 100,000 rpm, 60°F ambient temperature and 1628°F turbine exit temperature was 95.2 lbs.

Maximum thrust measured with augmentation was 150 lbs. This was achieved at an ambient temperature of 54°F, turbine exit temperature of 1630°F, a reheat temperature of 2650°F and a water/methanol flow rate of 4.5 lbs per minute. Combustor flameout prevented testing at the desired water/methanol flow rate. Correcting to sea-level pressure and adjusting for improved water/methanol performance at 59°F ambient temperature yields a thrust of 157.7 lbf. and an augmentation ratio of 1.586.

The ablative liners demonstrated lifetimes adequate for the intended mission. Both exit- nozzle configurations (coated graphite and refractory furnace cement) also proved adequate.

Test results demonstrate that a thrust-augmentation ratio of 1.57 can be achieved with the TJ-90 engine and that additional augmentation is possible if the combustor can be redesigned to accommodate water/methanol injection without flaming out.

2.0 OBJECTIVES

The overall objective of the program was to design, fabricate and demonstrate a thrust-augmentation system for an expendable turbojet that would double thrust at sea level on a standard day. Two constraints were imposed:

- The augmentation ratio must be achieved without increasing turbine-inlet temperature.

- The augmentation ratio must be achieved without increasing physical engine speed.

Achievement of this overall objective resulted in the following technical accomplishments:

- Baseline performance testing of a Sundstrand TJ-90 engine.
- Design, fabrication and test of a water-cooled dump-combustor afterburner.
- Design, fabrication and test of a water/methanol injection system.
- Design, fabrication and test of a thin-wall noncooled afterburner.
- Evaluation of refractory liner materials for the noncooled afterburner.
- Design, fabrication and test of refractory exit nozzles for the afterburner.

3.0 CONCLUSIONS

Based upon test results, the following conclusions can be reached:

- An augmentation ratio of 1.586 under standard-day conditions is possible with the Sundstrand TJ-90 engine if water/methanol injection and exhaust reheat are employed simultaneously.

- Small highly-loaded combustors such as the one on the TJ-90 are very sensitive to disruptions in mixture ratio of fuel and air and can suffer flameout if excessive water/methanol enters the primary region.

- Dow Corning 93-104 Ablative-silicone material is a satisfactory protective liner material for the afterburner for temperatures up to 3000°F if mission time is less than 10 minutes.

- Super 32 Castable Refractory Furnace Cement, manufactured by Pryor-Giggey of Pueblo CO is a suitable liner material for the afterburner with durability exceeding that of Dow Corning 93-104. Weight considerations may limit its use to ground test only.

- Super 32 Castable Refractory Furnace Cement is not suitable for use in exit nozzles at temperatures exceeding 2900°F due to its tendency to melt near the nozzle inlet and redeposit at the throat, inducing blockage.

- Graphite is a suitable nozzle material if it is coated to prevent oxidation. Sodium silicate solution was used to coat the nozzle and performed admirably for periods up to 5 minutes.

- Direct injection of water/methanol into the afterburner tended to reduce thrust. It appeared that heat loss due to evaporation was greater than heat available from methanol combustion at the prevailing oxygen levels in the afterburner.

- Achievement of augmenter temperatures above 2970°F may not be possible with full water/methanol injection.

- Improvement of engine compressor performance due to water/methanol injection was not as great as calculated. Compressor pressure ratio increased from 4.75 to 5.13 which is less than the calculated value of 5.77 from modeling.

- Overall augmenter performance is very sensitive to achieving a good match between compressor and downstream nozzles at the turbine inlet and afterburner exit.

4.0 RECOMMENDATIONS

The following is recommended if future development is to be done on this thrust-augmentation concept:

- A variable exit nozzle should be fashioned to allow fine adjustment of the afterburner exit area during testing. This will aid in maximizing thrust for a given engine speed and water/methanol flow rate.

- Modification of the TJ-90 combustor should be investigated as a means of increasing stability to allow introduction of water/methanol in larger quantities. If length is increased, the fluid can be introduced downstream of the primary region with sufficient residence time to completely mix and burn before entering the turbine nozzle.

- A detailed analysis of the reaction chemistry in the afterburner should be done to learn why temperatures were limited during operation with water/methanol. Basic calculations indicate that the 3200°F temperature should have been achievable.

- Methods of providing additional oxygen to the afterburner should be investigated. These include chemical additives, such as nitrates and peroxides, and methods of pumping ambient air into the burner.

- An engine speed control should be employed to reduce workload on the operator.

- A real time digital data acquisition system should be employed when testing engines of limited life.

- The heavy-wall afterburner should be designed with the split line running longitudinally to allow easy inspection, modification and refurbishment of the interior.

5.0 BACKGROUND

Lower thrust sustainer engines for missiles and drones often lack sufficient power for takeoff or dash capability. Solid-rocket boosters are often employed to accelerate these vehicles to flight speed.

5.1 Statement of Work

Employment of a single-integrated propulsion system capable of high thrust for initial boost and efficient low thrust for sustainer operation will eliminate the need for the booster. Such a system would have the additional capabilities of throttleability and restart, which solid rockets do not possess. A thrust augmenter, incorporated as an integrated part of the air-breathing propulsion system, would provide a highly flexible boost/sustain system for tactical missiles and drones.

M-DOT originally proposed to combine exhaust reheat with water/methanol injection to augment thrust of a turbojet engine 100%. Following is background information on the two concepts.

5.2 Thrust Augmentation Through Exhaust Reheat

Turbojet thrust augmentation through exhaust reheat has been in common use for 40 years. The basic principle involves increasing energy of a fluid stream by increasing temperature at constant pressure. Doing so at constant pressure implies that energy content of a turbojet-exhaust stream can be increased without increasing turbine backpressure and altering basic cycle parameters. The resulting increase in exit velocity results in increased thrust if pressure and mass flow are fixed. If the effects of added fuel mass are neglected, thrust increase is roughly proportional to the square root of the ratio of absolute temperatures before and after reheat. If cycle parameters and geometry are fixed upstream of the reheat burner, a larger diameter nozzle is required to pass the exhaust flow.

Several studies have been conducted by F. D. Stull and R. R. Craig on the concept of the dump combustor. Dump-combustor afterburners were built and tested on turbocharger-based turbojet engines by J. A. Poier and R. Dotan at the Air Force Institute of Technology (References 1 and 2) and by C. F. Baerst and J. W. Sanborn at AiResearch Manufacturing Co. of Arizona. (Reference 3). A dump combustor is essentially a round tube with an abrupt increase in diameter near the entrance. Gas entering the tube at the small end forms a recirculating zone at the discontinuity, which serves to stabilize combustion within the tube. The dump combustor is the simplest of afterburner designs and the lowest in cost. A disadvantage is added length required for complete mixing and combustion.

Dotan, in Reference 1, reported an augmentation ratio of 1.48 with this type of combustor but this was accomplished with a relatively low entrance temperature of approximately 1500 to 1550°F. Baerst and Sanborn achieved a ratio of 1.43 with an entrance temperature near 1545°F.

Investigations by M-DOT of the TJ-90 configuration confirmed known performance data on the

engine and predicted an augmentation ratio of 1.33 at an exit temperature of 3200°F. This ratio is lower than that achieved in the previously referenced reports because the TJ-90 operates at a significantly higher turbine exit (afterburner entrance) temperature than the other engines. Reference 2 test results indicate that a .5 inch step for the flame holder will yield optimum performance. Length to diameter ratio as a variable was studied by Dotan. 3.5 was found to be optimal but a reduced ratio of 3.0 resulted in little performance loss. Most of the designs studied utilized shear atomizing fuel nozzles located upstream of the step. Criteria for establishing augmentation ratio was to maintain constant gas horsepower (temperature, pressure and flow rate) at the turbine exit. For work conducted in the referenced materials, this was accomplished by maintaining a 1700°F turbine-inlet temperature for all tests.

5.3 Thrust Augmentation Through Water/Methanol Injection

It has been known for 60 years that injection of a mixture of water and alcohol into an internal combustion engine can delay the onset of detonation and allow higher compression ratios to be employed. This is due to cooling of the engine inlet air and to the anti-detonant qualities of the water/methanol vapor. A higher compression ratio increases power capability of the engine. As a general rule, gas turbine engines can also realize power augmentation through water/methanol injection but for the following reasons:

- O Injection of fluid at the engine inlet results in cooling of the inlet charge, thus increasing density and, therefore, mass flow rate through the engine.

- O Cooling of the inlet charge increases compression ratio by increasing corrected speed of the compressor rotor.

- O Turbine work increases for a given temperature drop due to increased mass flow. This reduces required pressure drop across the turbine and increases available pressure at the exit nozzle.

The above effects are slightly offset by a reduction in compressor efficiency that is proportional to fluid injection rate.

A study by P. M. Ardans and D. W. Stephenson (Reference 4), both of Garrett AiResearch presents an analytical method for the prediction of performance of gas turbines with water/methanol injection. The paper outlines the above effects and attempts to model the process thermodynamically. Charts presented in the paper show:

- O Effect of unevaporated fluid on compressor efficiency,

- O Predicted augmentation ratio for various fluid injection rates and ambient temperatures,

- O Effect of injection rate and ambient temperature on compressor pressure ratio and discharge temperature,

- O Effect of injection rate and solution composition on shaft horsepower.

The study also describes variation of the compressor operating line due to upstream and downstream injection.

For the specific case of the TJ-90 engine, study of estimated compressor characteristics indicated that the efficiency benefits of compressor flow reduction due to injection of fluid downstream of the compressor would provide a net increase in thrust.

5.4 The Sundstrand Turbomach TJ-90 Engine

The TJ-90 expendable-turbojet engine is derived from the earlier Gemjet which, in turn, was derived from the Sundstrand Turbomach Gemini T-20G-20 auxiliary power unit. Sundstrand Turbomach received a contract in 1986 from the U.S. Army Missile Command (MICOM) to provide a turbojet engine rated at 40 lbs thrust for use on the FOG-M missile. This model configuration was grown into the TJ-90 which is rated at 107 lbf. thrust at 103,000 rpm. This family of engines is characterized by the single piece "monorotor" (compressor impeller and turbine rotor in a single-piece casting) and "monostator" (compressor diffuser and turbine nozzle in a single-piece casting). Figure 1 below is a cross section of the TJ-90.

6.0 BASIC RESEARCH AND DESIGN

6.1 Engine Cycle Analysis

Engine cycle data was obtained from Sundstrand and consisted of recorded performance data from several engine test runs and a compressor map. This data was used to model engine performance and verify initial performance estimates made to support the Phase I proposal. Compressor characteristics were studied to estimate effects of water/methanol on compressor performance.

6.2 Afterburner Design

Due to simplicity of fabrication and a good database on design characteristics, the dump combustor afterburner was chosen for fabrication and testing. The afterburner consisted of entrance diffuser, burner and exit nozzle.

6.2.1 Aero/Thermodynamic Gas-Path Design

Design data from References 1, 2, and 3 were used to configure the afterburner. A step height of 0.5 inches was chosen based upon results cited in Reference 2. An aspect ratio of three was chosen based upon results cited in Reference 1. It was decided to incorporate an inlet diffuser to reduce burner inlet Mach number to 0.19. Although higher inlet velocities have been demonstrated, this lower value was chosen to reduce pressure losses.

Fuel nozzles were sized based upon a required fuel flow of 180 lbs per hour to attain 3200°F at the design point mass flow rate and on required depth of penetration of 17% of the duct diameter into the airstream. For the chosen airstream Mach number, fuel jet velocity was calculated to give required penetration and a required fuel pressure of 40 psig was calculated.

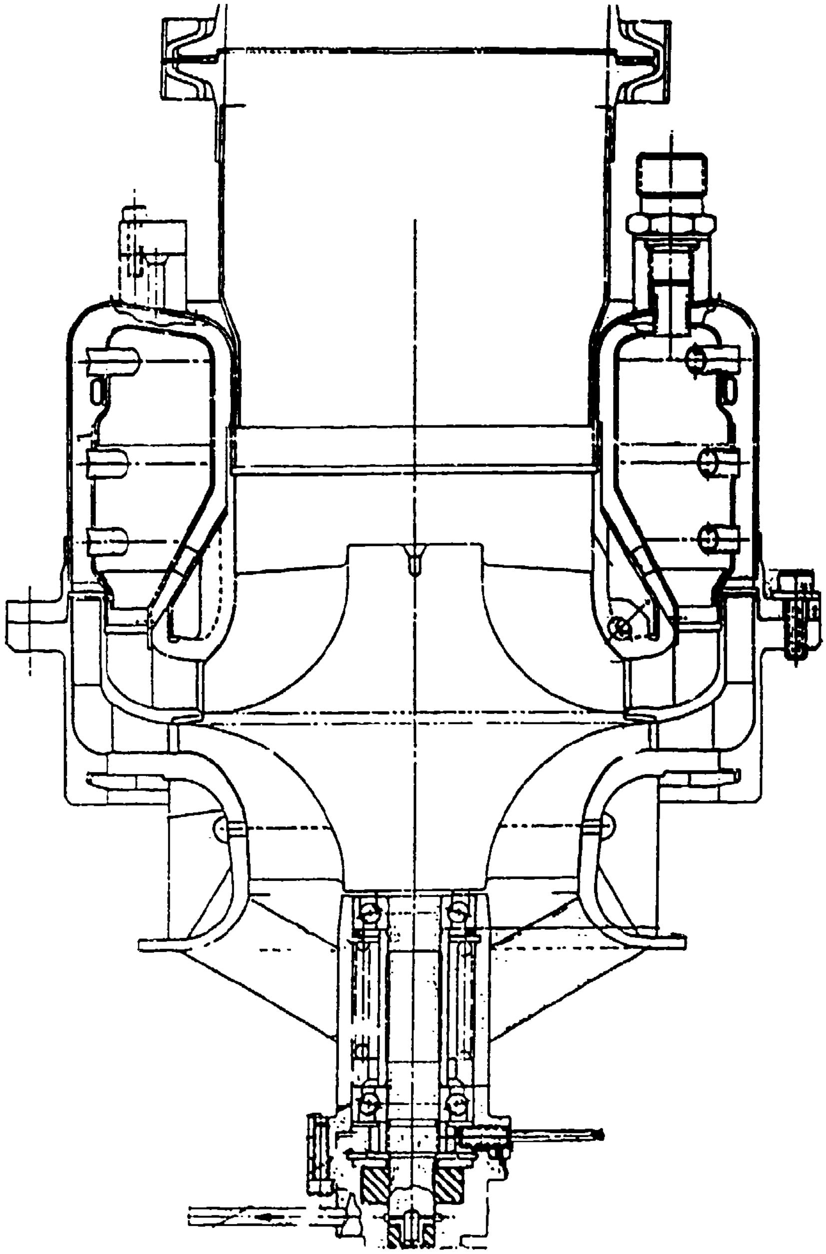

Figure 1 - Cross section of Sundstrand TJ-90 turbojet engine.

Diameter of the fuel nozzles was 0.02 inches. This fuel nozzle design results in an estimated local fuel/air ratio 3.7 times the overall ratio, thus insuring high stability. The ignitor was placed in a region where recirculation back flow was expected to occur. The initial exit nozzle had a straight-conical gas path. Due to excessive erosion, the design was modified to incorporate a radiused inlet and straight section at the throat. The straight section is undesirable from an aerodynamic point of view but increases available time at temperature before area increase occurs. Refer to Figure 2 for a scaled cross-sectional view of the afterburner. Overall design parameters for the afterburner are summarized below:

Inlet diameter	3.45 inches
Combustor inlet diameter (upstream of the step)	4.5 inches
Combustor diameter (downstream of the step)	5.5 inches
Area ratio	1.49
Combustion chamber length	17.0 inches
Gas velocity upstream of the step	406 feet/second
Combustor loading parameter	1.08
Design point exit temperature	3200°F

6.2.2 Exit Nozzle Sizing

The afterburner exit nozzle was sized to match compressor and turbine characteristics. To calculate this area, total cycle pressure was first estimated based on the TJ-90 compressor map. turbine exhaust pressure was then determined after achieving a power balance with compressor requirements and typical losses. Mach number in the afterburner is calculated and associated losses are subtracted from total pressure to yield pressure ratio across the exit nozzle. With the desired exit temperature known, required nozzle area can be calculated. For a temperature of 3200°F, total pressure of 33.7 psia. and total mass flow rate of 1.85 lbm per second, required nozzle exit area is 6.833 square inches.

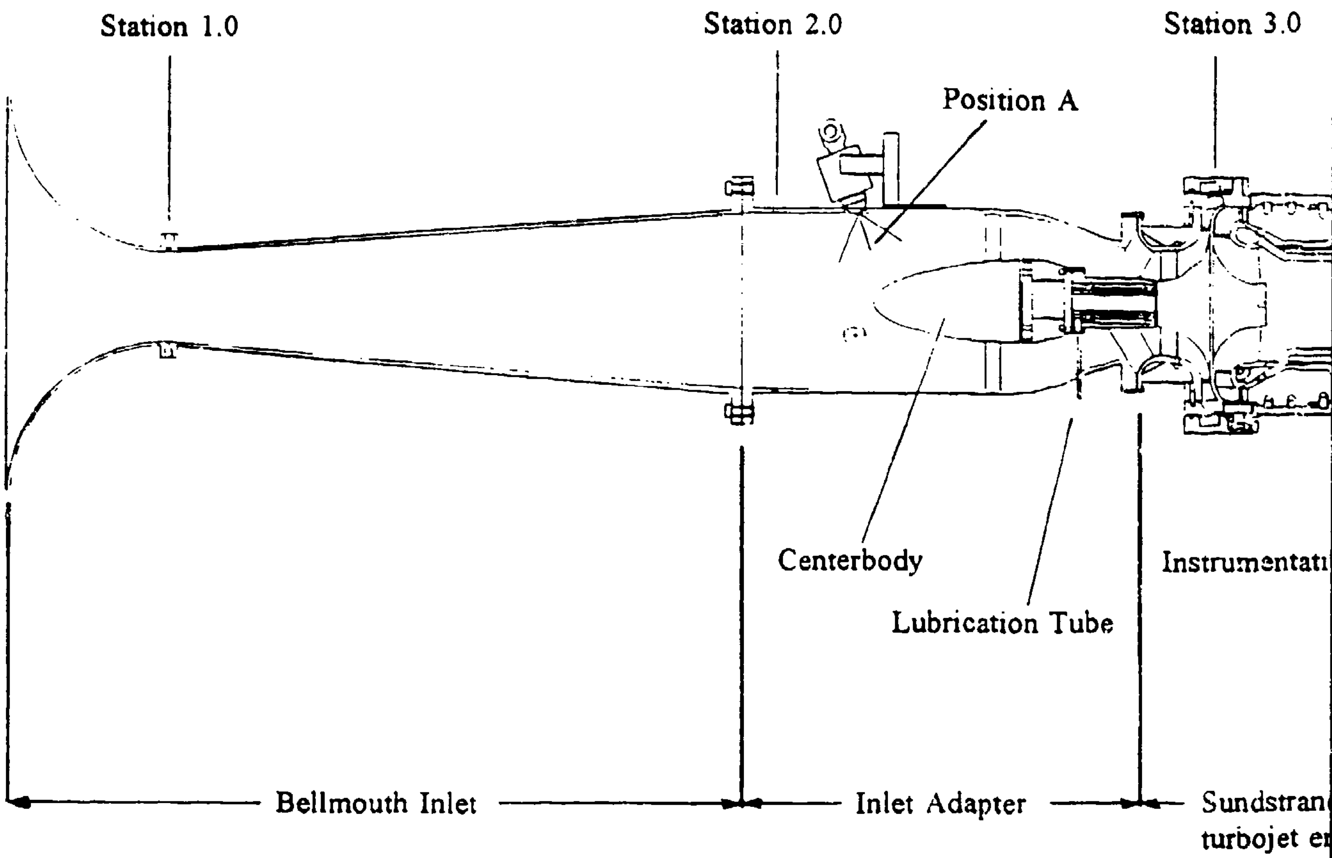

Figure 2 - Cross section of the co

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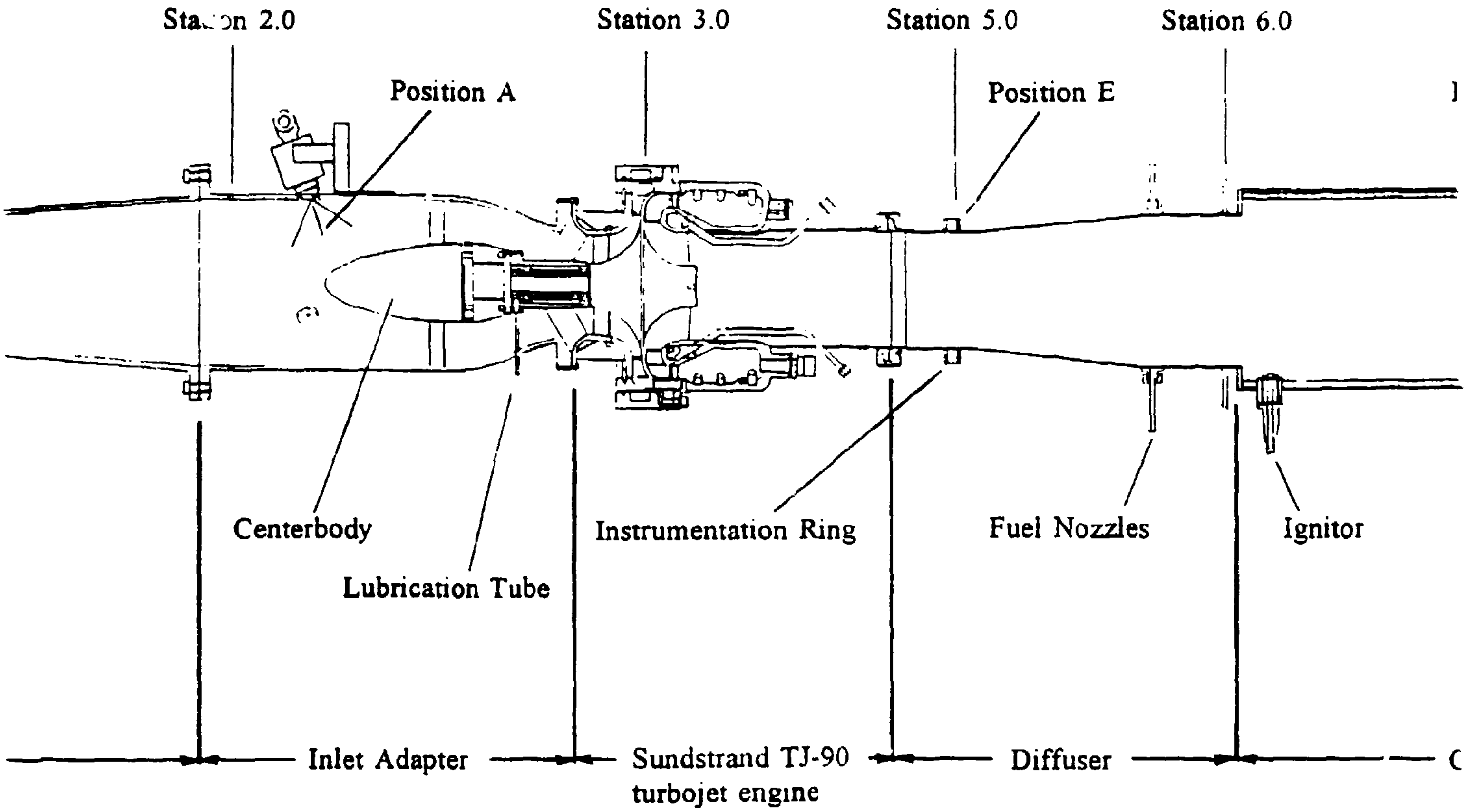
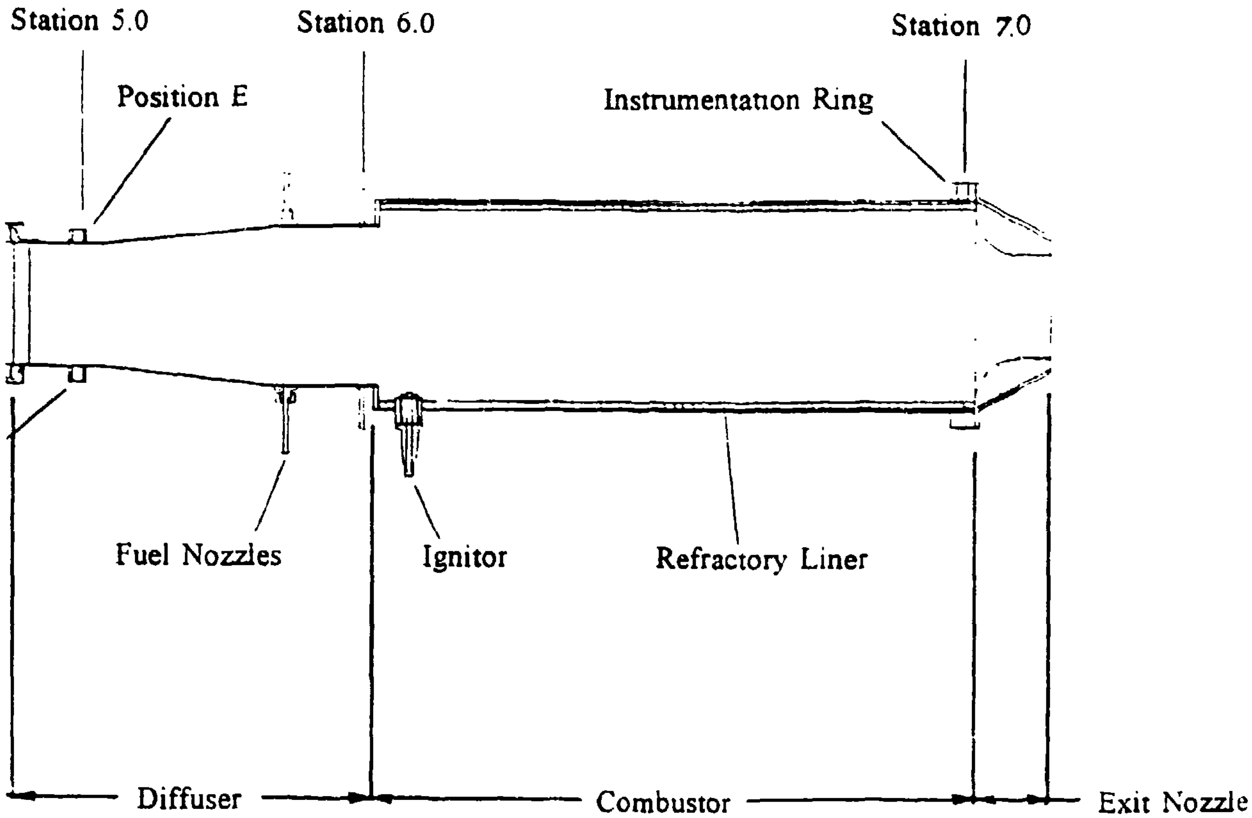


Figure 2 - Cross section of the complete engine/augmenter system.



ne/augmenter system.

6.2.3 Afterburner Hardware Design

Due to successful operation of a water-cooled afterburner in References 1,2 and 3, this configuration was initially chosen for performance testing. The combustor was of a double-wall construction with a coiled baffle sandwiched between inner and outer walls. The baffle served as a guide for the cooling water, forcing it to flow in a spiral pattern. Water circled the liner several times before exiting at the rear coolant fitting. (See Figure 3.) It was intended that this design would be used for all performance testing. However, failure of the inner liner early in the program resulted in the decision to use ablative and refractory liners for the remainder of performance testing.

Two ablative/refractory coatings were tested. The first was a silicone-based substance manufactured by Dow Corning called 93-104. It is a room-temperature or elevated-temperature cure silicone with a fibrous-silica filler. The other coating tested was Super 32 Castable Cement manufactured by Pryor-Giggey of Pueblo CO. It is an alumina based ceramic that comes as a powder to be mixed with water. Details on the use and application of these two products can be found in section 6.4.

A water-cooled exit nozzle was ruled out because it was thought that several exit-throat areas would have to be tested before an optimal one was found. Graphite was chosen because it is readily available in rocket-nozzle grades and is easy to machine and reconfigure. After erosion was noted during testing, a protective coating of sodium silicate was tested with positive results. Also tested were nozzles cast from the Super 32 Cement.

6.3 Water/Methanol Injection System Design

Design of the water/methanol injection system was based upon data presented in Reference 4 and upon known characteristics of liquid evaporation in a shearing air stream.

Water/methanol injection was evaluated at four flow path locations.

- *Eight inches upstream of the compressor (Position A on Figure 2)* -- Fluid was injected through three centrifugal-atomizing nozzles. Rated flow rate of each nozzle was 15.3 gallons per hour and cone angle was 80°. The centerline of each nozzle cone was canted 20° aft and approximately 35° tangentially to the flow stream. Canting in the tangential direction was done to induce a slight swirl in the inlet air stream to increase dwell time of the fluid prior to entry into the compressor. This helped promote evaporation.

- *Immediately upstream of the compressor-deswirl vanes (Position B on Figure 4)* -- Twelve .025 inch diameter holes were drilled radially through the monostator housing to serve as nozzles. An aluminum ring was machined to fit on the monostator; centered over the nozzles forming an annulus for the fluid. O-rings provided a fluid-tight seal between the ring and the housing. An in-line filter was located at the annulus inlet. Injection at this location would cause engine flameout prior to achieving the projected flow rate. This prompted reevaluation of this injection point and testing of the configuration outlined below.

Figure 3 - Water-cooled combustor prior to assembly.

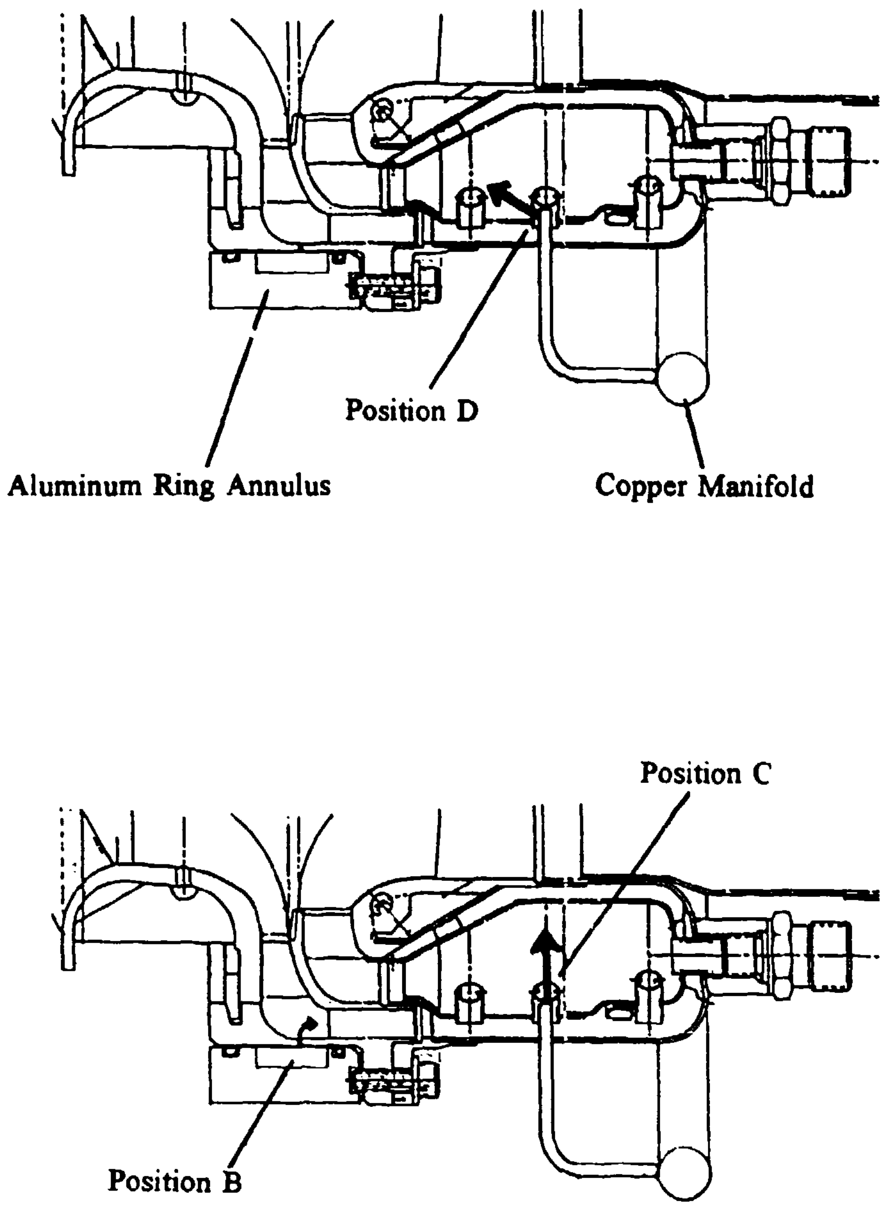


Figure 4 - Detail of combustor cross section with water/methanol injection points.

- O *Radially into the dilution zone of the combustor (Position C on Figure 4)* -- Twelve 0.025 inch diameter nozzles were located at the first row of dilution holes. The nozzle tubes extended radially outward from approximately 1/16 inch inside of the combustor wall through the plenum to an external copper manifold. The nozzles were silver soldered to the plenum casing and to the copper manifold. An in-line filter was located at the inlet to the copper manifold. Fluid flow was directed radially inward across the face of each first-row dilution hole such that air entering the hole would atomize the fluid through a shearing action.

- O *Axially into the dilution zone of the combustor (Position D on Figure 4)* -- Because flameout was experienced with the above configuration, the nozzle ends were reconfigured to direct fluid in the direction of the airflow (towards the turbine inlet).

- O *Immediately downstream of the turbine exit (Position E on Figure 2)* -- Four 0.055 inch diameter orifices, previously used to measure static pressure at station 5.0, were used to inject fluid radially into the afterburner.

6.3.1 Aero/Thermodynamic Gas-Path Design

The goals in designing the compressor inlet were to provide sufficient dwell time for required evaporation of the water/methanol droplets and to generate as little flow distortion as possible at the compressor inlet eye. Average particle size was estimated to be less than 5 μm. At the prevailing ambient temperature of 59°F, evaporation time is approximately 6.0 milliseconds. Areas in the inlet adapter section were chosen to provide this dwell time. Mach number at the fluid injection point was 0.14. It was intended that dwell time would be sufficient for complete saturation of the inlet air prior to entering the impeller. Once in the impeller, additional evaporation of the larger droplets would occur as static temperature increased. Canting of the nozzles was done to provide a slight inlet swirl angle to further increase dwell time and to increase uniformity of mixture entering the compressor. The flowpath area downstream of the injection nozzles is constantly decreasing to provide constantly accelerating flow. This decreased the tendency for local areas of diffusion to occur thus reducing losses and distortion.

The compressor section was not modified other than to add water/methanol injection nozzles in front of the axial deswirl vanes. To estimate performance with water/methanol injection, compressor design data from Sundstrand was studied and aerodynamic parameters of the basic compressor determined at the following critical points in the flowpath:

- O Impeller inlet and outlet
- O Diffuser inlet and outlet
- O Deswirl inlet and outlet

Flow angle, Mach number, velocity ratio and pressure recovery were calculated for each of these points at 100% speed. These basic characteristics were then used to estimate flow parameters in each element. Blockage at the impeller exit and outlet swirl were iterated until the relative flow angle exiting the impeller deviated 3° to 6° from the blade angle. Combined, these relationships formed a basic model of the TJ-90 compressor that was used to predict performance with water/methanol injection. To predict performance with injection, the impeller

flowpath was divided into ten incremental stations. At each increment, pressure, temperature and vaporization were estimated and used as input to the next incremental stage. Impeller exit conditions and estimated efficiency were thus determined. For purposes of this calculation, a polytropic efficiency penalty of 3% was assumed. This entire process was accomplished iteratively using Fortran computer code.

The above calculations, along with earlier hand calculations, indicated that benefits of compressor injection would be slightly offset by relocation of the operating point further to the right on the compressor map. Shifting the operating point further to the left into the higher efficiency region of operation would provide additional performance benefits by increasing compressor efficiency. To calculate required water/methanol flow behind the compressor, an iterative process was used wherein compressor ratio was estimated at the desired operating point and mass flow calculated based upon existing turbine inlet and afterburner exit geometries. This mass flow was compared with the non-augmented mass flow with the difference being required water/methanol flow. This flow was then added to the flowpath downstream of the compressor and performance estimated again using the above model. Iteration was complete when the initial and final performance points matched.

It was decided that fluid would be injected immediately upstream of the compressor deswirl vanes in order to maximize dwell time prior to entering the burner.

Below is a summary of predicted operating conditions for the compressor:

Compressor inlet pressure	14.7 psia.
Compressor inlet temperature	59°F
Compressor air flow	1.6 lb/second
Water/methanol flowrate	0.08 lb/second
Compressor outlet pressure	85.1 psia
Compressor outlet temperature	354°F
Compressor pressure ratio	5.79

6.3.2 Water/methanol Injection System Hardware Design

Due to their low cost, ready availability and variety of configurations, furnace fuel nozzles were chosen for injecting fluid upstream of the compressor. To get complete coverage of the inlet plane, three nozzles with 80° cone angle were chosen. Maximum flow capacity was 15.3 gallons per hour per nozzle. Nozzles were mounted on gimbals to allow canting in the desired direction and fine adjustment of angle during testing. Nozzles were manifolded together using copper tubing and brass compression fittings.

6.4 Refractory Coatings and Materials

High-temperature material selection was based on the calculated 3200°F temperature and 500 ft/sec gas velocity that the combustor tube would be exposed to. Dow Corning 93-104 ablative material was selected because its primary use is for high-shear, high-heat-flux environments such as rocket nozzles and spacecraft reentry heat shields. This material can withstand temperatures up to 6000°F for several minutes and has low thermal conductivity. Upon contact with high-velocity high-temperature gases, silica fibers mixed with the silicone melt to form a protective glaze. A special primer is used to treat the metal surface prior to application. Material was applied to the interior of the afterburner using a spatula and distributed over the surface by spinning the burner in a lathe as the material was cured. Figure 5 shows a sample test article coated in this manner. The coating thickness was approximately 0.2 inches. The exit nozzle also required a high-temperature material. Rocket-nozzle-grade graphite was chosen because of its low thermal conductivity and low cost. Later in the program, after the graphite and 93-104 had been used up, Super 32 Castable Cement was chosen to replace both the ablative silicone and graphite. It was applied to the interior of the burner in a layer approximately 0.2 inches thick. Nozzles were cast using a fiberglass mold made from one of the graphite nozzles. Nextel® ceramic cloth manufactured by 3M was used to bed the nozzle into the retainer cone and to seal the exit nozzle flange.

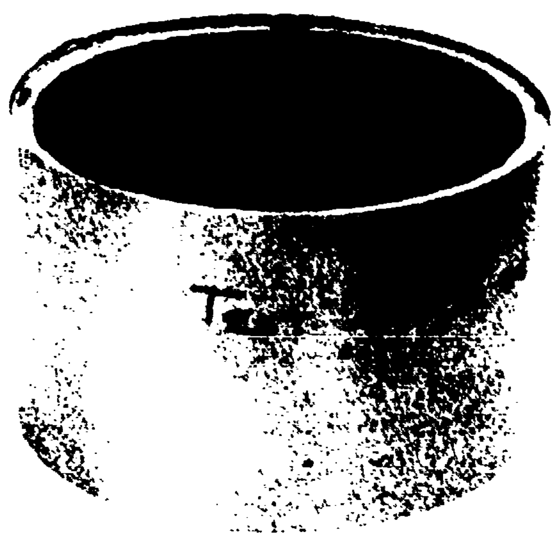


Figure 5 - Dow Corning 93-104 ablative coating test article.

6.5 Laboratory Fixtures

M-DOT designed and fabricated all test fixtures needed to test the engine. The following describes in detail, the hardware designed for this program.

6.5.1 Water/Methanol Delivery System

This system consisted of a 12-stage electrically-driven centrifugal pump, relief valve, pick-up tube with screen, and pressure gauge, all mounted on a tubular stand. Height of the stand was such that a five-gallon bucket of fluid could be placed directly underneath.

6.5.2 Test Stand Adapters

Hard engine mounts were designed to attach at the engine casing flange. Vertical struts were used to position the engine centerline the proper distance from the thrust-platform pivot. A steel beam was used to balance and support the lengthy inlet assembly and reheat section. It consisted of a 1.5 inch square tube with mounting feet and incorporated machined-aluminum vertical supports. The vertical supports were attached to the tube using all-thread rod so that support of each member could be adjusted. Configuration of the support is plainly visible in Figure 6.

6.5.3 Inlet Bellmouth

The inlet bellmouth design was based upon guidelines set forth in AEDC-TR-68-22, "Accurate Measurement of Airflow Rate During Tests of Air-Breathing Propulsion Systems", published by the Air Force Systems Command (Reference 5). Throat area was chosen to yield a Mach number of 0.68 and a corresponding pressure signal of 4.5 psig at 100% engine speed.

6.5.4 Starting System

Start air was supplied by a 10 HP compressor with 80 gallon receiver tank. Air lines to the test stand were plumbed with ¾ inch schedule 40 pvc pipe. A ½ inch ball valve was used to control air delivery.

7.0 HARDWARE FABRICATION

The afterburner and water/methanol injection systems were fabricated by M-DOT as were all test fixtures. Construction details follow.

7.1 Afterburner

The diffuser section was fabricated from 16 gauge type 347 stainless sheet metal and consisted of two straight sections and one conic section. Individual sections were sheared, rolled and tack welded. They were then positioned together using aluminum tooling jigs and welded. A marmon flange and instrumentation ring were machined from 347 stainless-steel bar stock and welded to the inlet end of the diffuser straight section. Stainless-steel compression fittings were then welded to the exit end of the conic section to hold the fuel nozzles.

Figure 6 - Engine and augmenter on test stand

⅛ inch diameter stainless steel tubing was used for pressure leads which were welded just downstream of the fuel nozzle ports. The two fuel manifolds each consisted of four ⅛ inch diameter type 304 stainless-steel tubes of equal length silver brazed to a drilled inlet block. A static pressure manifold was made for the instrumentation ring at station 5.0 using four ⅛ inch diameter type 304 stainless-steel tubes and compression-to-NPT fittings.

The same diffuser section was used for both water-cooled and ablative lined combustor sections.

7.1.1 Water-Cooled Combustor Tube

The water-cooled combustor tube was of double-wall construction with flanges at both ends. The inner tube was sheared , rolled, and welded. A ¼ inch diameter tube was then coiled and stitch welded to the liner. (See Figure 3.) The ignitor boss was machined from type 304 stainless steel and welded to the inner liner. The forward flange was welded to one end of the inner liner before the outer liner was slid over the assembly and tack welded into place. Eight holes were drilled through both liners ⅜ inch upstream of the exit plane of the combustor tube. Eight bosses were machined from type 304 stainless steel inserted into the holes and welded. The complete assembly was then TIG welded using back-up gas. The rear flange was then machined and welded to the exit end of the tube for mounting the exit nozzle.

7.1.2 Refractory-Coated Combustor Tube

The non-cooled combustor tube was constructed of 0.063 thick type 347 stainless-steel sheet with machined flanges welded to each end. The exit flange was made so that the exit nozzle could be attached to it in the same fashion as with the water-cooled design. To verify adhesion and test the application process, a test section was made from stainless steel. (See Figure 5.) Application was accomplished by trowelling a premeasured amount of mixed material onto the interior of the tube and spinning the tube in a lathe to centrifugally distribute the material and flatten it into an even layer. The tube was then heated while still spinning to cure the material.

To coat the tube with Super 32 Castable Furnace Cement, a collapsible sheet-metal inner liner was fashioned and piloted in the center of the tube. The annulus between tube and liner was then packed with cement using a tamping rod. After cure, the inner liner was collapsed and removed. The cement was then post cured by directing the jet blast from a kerosene shop heater through the tube for several hours.

7.1.3 Graphite Exit Nozzle

The exit nozzle was machined from a 6 inch diameter piece of rocket nozzle grade graphite using a lathe. A vacuum cleaner hose was placed near the cutting tool during machining to capture the graphite dust.

To coat the nozzle, sodium silicate solution was brushed onto the flowpath surface and allowed to air dry. An enclosure was then constructed of furnace bricks and an oxygen/acetylene torch used to heat the nozzle a few hundred degrees to remove all water from the coating. The torch flame was then directed against the surface to fire the material into a fine glaze.

7.1.4 Cement Exit Nozzle

The cement nozzle was cast in a fiberglass mold. To make the mold, the graphite nozzle was inserted into the metal retainer casing and used as a mandrel for a fiberglass layup. After cure, the retainer casing flange bolt-hole pattern was transferred to the fiberglass lay-up and the graphite was removed. The fiberglass mold was bolted to the metal casing and Super 32 Castable Cement was packed into the void using a tamping rod. After a 24 hour initial cure, the nozzle was baked for several hours at 500°F to remove water. Finally, the nozzle was fired for two hours in a kiln at approximately 2200°F. This produced a nozzle with a very smooth flow-path surface and a close-tolerance fit into the retainer cone. See Figure 7.

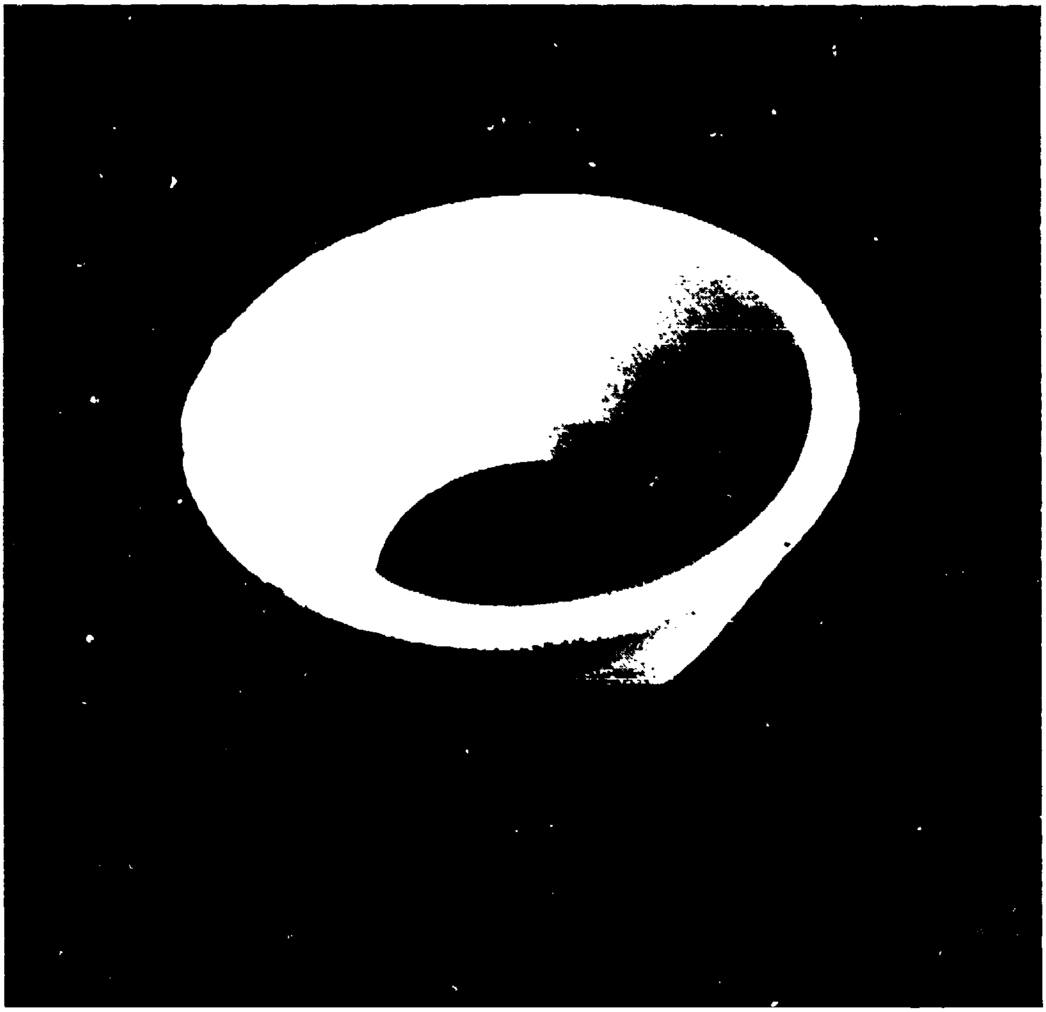


Figure 7 - Refractory cement afterburner nozzle.

7.2 Water/methanol Injection System

Hardware for mounting the nozzles was machined from cold rolled steel and welded. The manifold for injection upstream of the deswirl vanes was machined from 6061 T6 aluminum bar. The manifold for combustor injection was formed in ½ inch diameter copper tube using a tubing bender. The components were then silver soldered together.

7.3 Engine Modifications

Engine modifications were required to mount the afterburner, combustor water/methanol injection manifold and to facilitate starting and assembly/disassembly. All modifications were accomplished at M-DOT.

7.3.1 Start Air Manifold

The Sundstrand TJ-90 turbojet engine start air system consists of two impingement holes in the turbine shroud connected to two ¼ inch diameter tubes exiting the engine through the tailpipe. To facilitate installation of the afterburner and to improve start performance, tube length was shortened from 2 feet to 1 foot and tubes were made to exit the gas path radially through the wall of the tailpipe. External to the tailpipe, the tubes were joined by a manifold to a single start-air fitting. To allow disassembly of the engine for inspection, the tubes were cut prior to exiting the tailpipe and machined couplings installed. The resulting slip-fit air seal at each joint was more than adequate to allow engine starting.

7.3.2 Tailpipe

Incorporation of the above mentioned start-air manifold modifications resulted in a 3.0 inch reduction in tailpipe length.

7.3.3 Fuel Pump

To simplify lubrication and control requirements, the engine-mounted fuel pump was removed and a remote electric pump was used to supply fuel under pressure to the control stand. From the control stand, flexible hoses conducted fuel to the engine and afterburner manifolds.
A machined aluminum plug was installed in place of the engine-mounted pump to seal the pump and bearing cavity. A fiberglass fairing was used to reduce gas-path drag of the plug.

7.3.4 Burner Modifications

Midway through the test program, the engine became very difficult to start. After consultation with Sundstrand, it was decided to disassemble the engine and inspect hardware for indications of a possible cause. The burner was found to be distorted where it pilots into the turbine-inlet shroud. The part was reworked to meet drawing specifications and reinstalled. No more start problems were experienced.

7.3.5 Water Injection Manifold

Holes were drilled radially in the combustor plenum and burner can to install the water/methanol injection nozzles. The twelve stainless steel nozzle tubes were then silver soldered to the plenum. Nozzle tubes were made from lengths of ⅛ inch diameter type 321 stainless steel tube. The end of the tube was chucked in a lathe and swaged down to close off the end. The closed end was then drilled to size.

7.4 Test Fixtures

7.4.1 Inlet Bellmouth

Inlet bell mouth venturi construction was of fiberglass with a machined aluminum insert at the venturi throat and a machined aluminum exit flange. The section was fabricated over a polished mahogany mandrel.

7.4.2 Inlet Adaptor Section

The inlet adapter section was fabricated from fiberglass with aluminum flange inserts at the inlet and exit. Holes were drilled radially through the wall at the inlet to accommodate the three water/methanol nozzles. The section was fabricated over a polished mahogany mandrel. The machined aluminum insert at the exit was hand machined to fit around the engine inlet struts and provide a smooth transition from the section to the engine inlet. A bullet-shaped fiberglass centerbody completed the assembly. It was centered in the flow path and was supported on four struts. Its purpose was to streamline flow around the engine bearing carrier.

A silicone-rubber boot was manufactured with the dual purpose of providing a good air seal around the inlet and soft mounting the venturi and adapter section to reduce vibratory stress. The part was vacuum-transfer molded in General Electric RTV 664 silicone rubber.

8.0 TESTING

Testing was conducted outdoors approximately 50 feet from the rear facility door. This permitted use of facility air and electricity while maintaining a safe distance between the building and engine for fire protection. The operator was seated at the engine control panel approximately 25 feet from the engine. Figure 8 is a photograph of a typical test setup. The operator's panel and water/methanol pump can be seen in the foreground.

Prior to each test run, instrumentation and shut down systems were calibrated using a signal generator and thermocouple voltage source.

Due to the expendable nature of the engine design, run time was minimized to reduce probability of turbine or bearing failure. Data were recorded immediately upon reaching the desired setpoint. On most of the test runs, the engine flamed out prematurely while the operator was increasing water/methanol flow rate to the desired level. As a result, very little data was obtained at high augmentation levels.

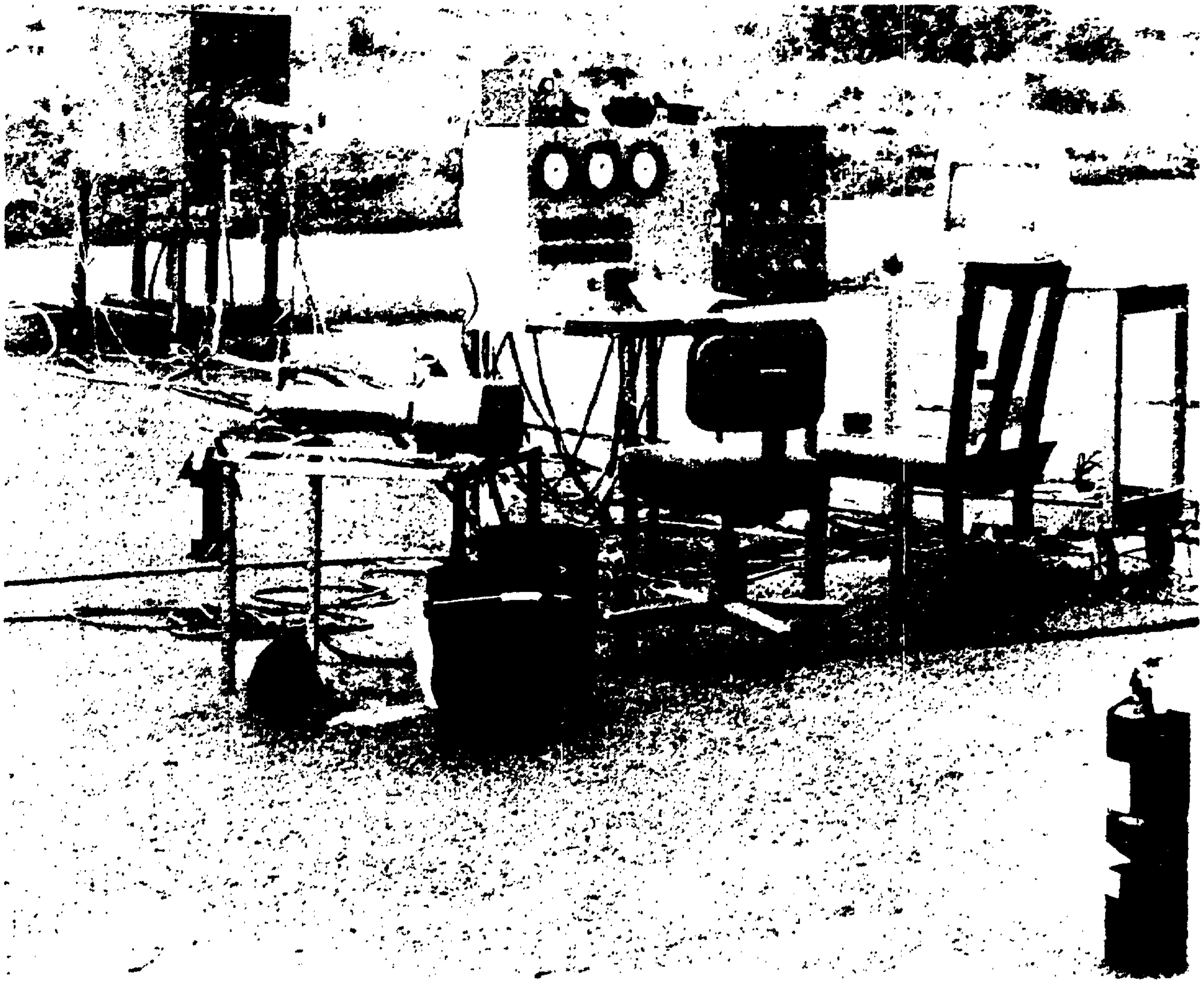


Figure 8 - Test set up.

8.1 M-DOT Test Facility

The test facility consists of test stand, control stand, and fuel delivery system.

The test stand uses a 500 lb. capacity strain-gauge load cell to measure the force applied to a hinged platform. Accuracy is ± 0.1 % F.S or ± 0.5 lbf. The platform was designed so that it could be leveled independently of the frame for zeroing the thrust reading prior to test. The stand is portable to allow remote testing. The stand was calibrated twice during the program using the chain and pulley set-up shown in Figure 9. Scatter shields were used to prevent injury in case of catastrophic engine failure.

Control stand instrumentation readouts consist of:

- Three factory-calibrated analog pressure gauges with an accuracy of ± 0.25 % F.S.
- Four calibrated digital temperature indicators with an accuracy ± 0.9° F.
- One digital frequency indicator with an accuracy of ± 1 least significant digit (LSD) or ± 2 ppm of input. This was used to measure engine speed and to operate the overspeed shutdown system.
- One digital thrust meter with an accuracy of ± 0.05% of reading or ± 1 count.

The test stand has four emergency engine shut-down systems: turbine overtemperature, mainshaft bearing overtemperature, engine overspeed, and low oil/air mist lubrication pressure. The stand is also equipped with five Hoke needle valves to manually control fuel and water/methanol flow. Fuel and water/methanol flow rates were monitored using calibrated turbine flow meters. Initial calibration of flow meters was performed out-of-house using Jet-A aviation kerosene. Two flow meters were later calibrated by M-DOT for measuring water/methanol flow.

The fuel delivery system consisted of a 55-gallon drum on casters, ⅓ hp. electric motor, 90 gph pump, relief valve, pressure gauge, and 20-micron filter. This unit was positioned 20-30 feet away from the engine and operator during testing. It provided a fuel pressure of 120 psig.

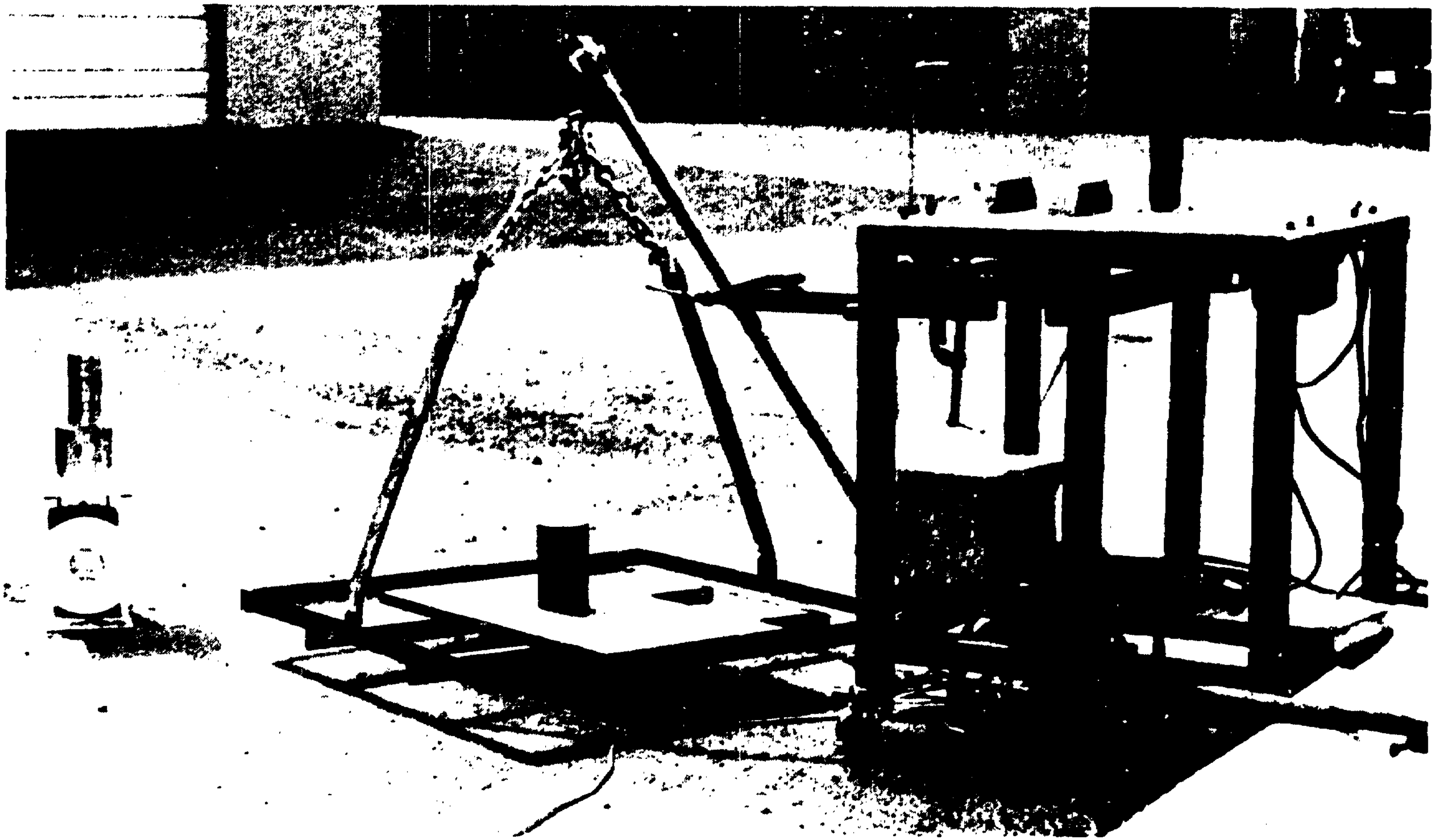


Figure 9 - Thrust stand calibration.

8.2 Instrumentation

In addition to the test-stand thrust cell, the following performance instrumentation was used:

One type K (chromel-alumel) thermocouple at station 1.0 to measure total temperature.
One type K thermocouple at station 3.0 to measure total temperature.
Four type K thermocouples at station 5.0 to measure total temperature.
Two type B (platinum rhodium) thermocouples at station 7.0 to measure total temperature.
Two static-pressure taps at station 1.0.
Two static-pressure taps at station 2.0.
One static-pressure tap at the combustor plenum (station 3.0).
Four static-pressure taps at station 5.0.
Four static-pressure taps at station 6.0.
Four static-pressure taps at station 7.0.
Engine-shaft-speed magnetic pickup.
Main engine fuel flow rate.
Afterburner fuel flow rate.
Engine inlet water/methanol flow rate.
Combustor water/methanol flow rate.

In addition to the above, type K thermocouples were installed on the mainshaft bearing outer races as a safety precaution to alert the operator of impending bearing failure.

8.3 Engine Operating Limits

The following operating limits were observed during testing:

Engine speed	102,000 rpm
Turbine exit temperature	1720°F
Mainshaft bearing temperature	150°F
Air/oil pressure	20 psig. minimum

8.4 Water/Methanol Fluid Preparation

Industrial-grade methanol and ordinary tap water were used for testing. A calibrated 70 lb. capacity scale was used to measure by weight, 25.2 lbs of water and 14.8 lbs of methanol into a five-gallon bucket to form a solution containing 63% water and 37% methanol. The fluid was mixed and covered to prevent evaporation.

8.5 Engine Starting and Operation

Engine starting was accomplished as follows:

- O Air pressure in the compressor receiver tank was brought to 175 psig.
- O Air flow to the bearing lubrication and cooling system was turned on and an assistant to the operator monitored the oiler to verify oil flow prior to start initiation.

- On a signal from the engine operator, the start assistant turned on the ball valve at the test stand and spooled up the engine.

- The test stand start system would then automatically turn on the master fuel solenoid and ignition when engine speed reached 5000 rpm.

- The operator opened the engine fuel control valve, awaited ignition and then modulated fuel flow to bring the engine to idle.

- The assistant then closed the ball valve slowly as the engine approached idle speed. If a deceleration or hung start occurred, the air valve was reopened until idle speed was reached. During start attempts early in the program (prior to rework of the burner can), it was necessary for the assistant to insert a fist into the inlet bellmouth to keep the engine from flaming out during start acceleration. This was done in an attempt to enrich the primary region of the combustor by reducing airflow. It is not known if this is what actually occurred in the engine. Nonetheless, the action did prevent blowout and could also be used to relight the engine if flameout occurred.

Once the operator and assistant gained experience starting the engine, warm starts could be accomplished with only 100 psig air pressure in the compressor receiver tank.

During a typical test run, the operator controlled engine speed, afterburner temperature and water/methanol flow by modulating twelve-turn needle valves. As afterburner fuel flow was increased, the engine speed would droop due to increased back pressure at the turbine. The operator therefore had to increase fuel to the engine to maintain the desired speed setpoint. Introduction of water/methanol also altered the engine-speed setting necessitating adjustment in primary-engine fuel flow to maintain the test set point. While the operator was maintaining the set point, one assistant was recording data and another was visually monitoring the engine on the test stand and liquid level in the water/methanol storage tank.

8.6 Engine Baseline Testing

Prior to conducting augmenter testing, the engine was run with a calibration nozzle supplied with the engine to establish baseline thrust. Thrust was measured at the following conditions:

Shaft speed	100,000 rpm.
Engine inlet temperature	51.7, 60.2, and 58.4°F for the three runs.
Base altitude	1107 feet.

Baseline tests were conducted three times during the program yielding three progressively higher thrust values. Because turbine-exit temperature also increased a proportionate amount, it is believed that nozzle exit area was decreasing as the nozzle distorted due to heat from the exhaust. Measurements of the nozzle after the runs confirmed that it had assumed an oval shape. Initial area was 6.83 inch^2. Exact final area could not be calculated.

The final baseline value of 95.2 lbf was used for calculating augmentation ratio.

8.7 Augmentation System Testing

During initial testing of the augmenter system, efforts were focused on obtaining the highest possible augmentation ratio. The engine was started and immediately accelerated to 100,000 rpm. The afterburner was ignited and exit temperature was set. Water/methanol was introduced first into the engine inlet and then into the compressor exit or combustor, whichever was set up prior to the run. Flameout generally occurred while water/methanol was being introduced after the compressor or into the combustor resulting in abortion of the test run. If flameout did not occur then turbine-exit temperature or afterburner condition was generally used as criteria for conclusion of the test run. Several runs were aborted when pieces of the afterburner were seen exiting the nozzle or when walls of the afterburner assumed a bright orange-yellow color indicating that failure of the protective liner had occurred.

The vast majority of performance runs ended in flameout and, as a result, few data points other than thrust and turbine-exit temperature were recorded at maximum augmentation. On test run 10, near the end of the test program, engine performance data were gathered at a thrust reading of 145 lbs prior to adding additional water/methanol and flaming out the engine. Data gathered during this run is presented in Table II below.

Flameout problems were still encountered when water/methanol injection was moved from aft of the compressor into the combustor at the first row of dilution holes. To remedy this situation, an alternate configuration was tested wherein the water/methanol was directed aft into the dilution region of the combustor. Testing of this configuration resulted in abnormally high turbine-exit temperature and lower engine performance. These tests generally ended when turbine-exit temperature exceeded established limits rather than from flameout.

Water/methanol injection was tested at the turbine exit in an attempt to achieve a predicted thrust increase due to increased mass flow. Results were disappointing with reduced thrust due to reduced reheat temperature.

A test was conducted wherein 37.5 % by weight of fertilizer-grade ammonium nitrate was dissolved in the water/methanol in an attempt to provide additional oxygen and prevent flameout. This test was aborted when turbine exit temperature exceeded limits but results were encouraging. Thrust at 92,000 rpm, 1620°F turbine exit temperature and 2613°F reheat temperature was 124 lbf.

The final three test runs were conducted to obtain detailed engine cycle data at a high augmentation ratio and to separate effects of afterburner and water/methanol injection. On the first, the engine was set at 100,000 rpm and the afterburner ignited. Data were recorded at a stabilized thrust of 140 lbs prior to increasing water/methanol flow rate and flaming out the engine. On the second, thrust was measured at station 7.0 temperatures of 2441, 2628, 2960, and 3002°F. Data were used to plot thrust augmentation ratio versus reheat temperature. (See Figure 10.) It should be noted that the final temperature reading of 3002°F may be incorrect since measured thrust more closely corresponded to that expected at 3200°F. On the final run, a constant reheat temperature of 2847°F was set and water/methanol flow rates varied. Results of this run can be found in Figure 11.

All testing was conducted with no significant damage to the engine. One minor incident did occur wherein a small piece of thermocouple lead detached from the aft bearing carrier and was ingested, causing slight damage to the tips of three impeller blades. Blade nicks were dressed out using a honing stone and testing was continued.

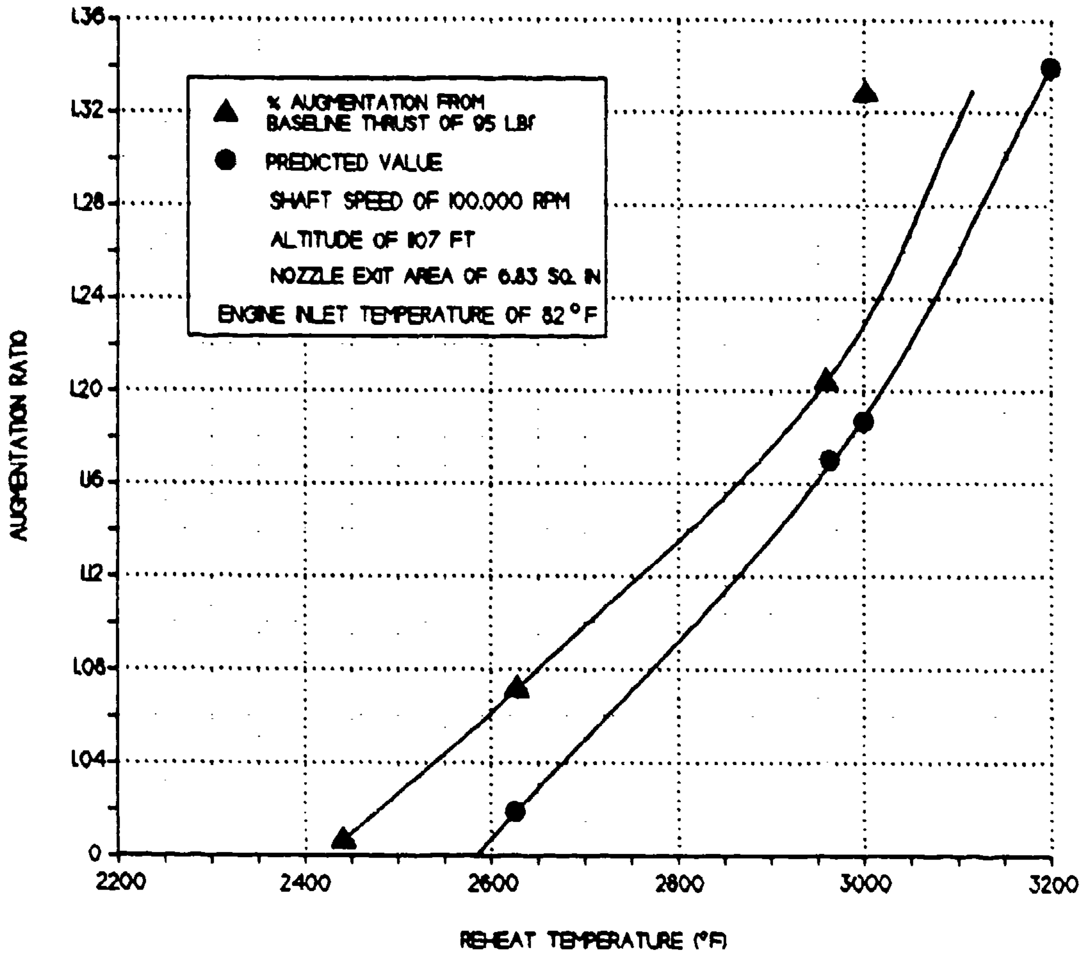


Figure 10 - Thrust augmentation ratio versus reheat temperature

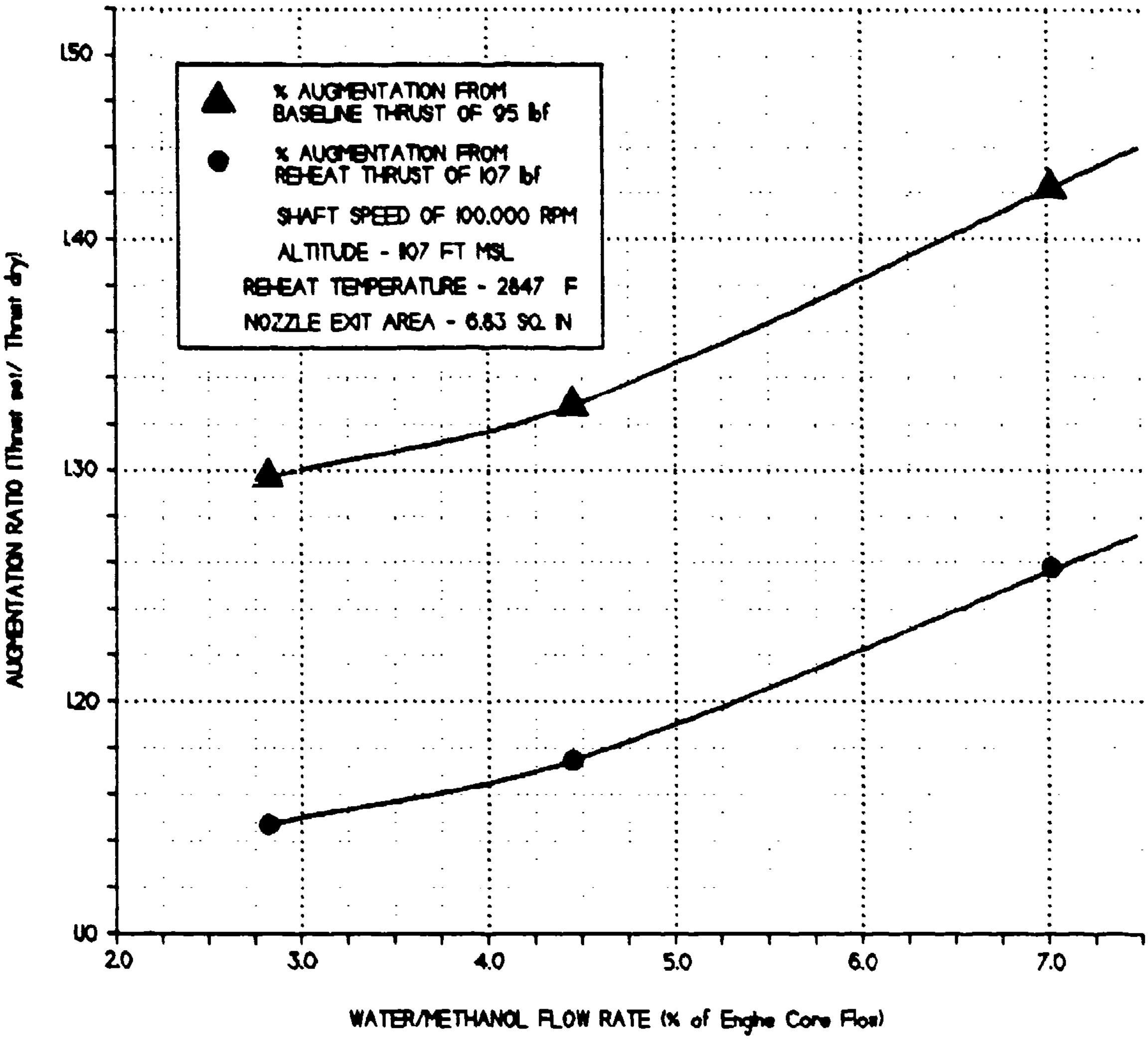


Figure 11 - Thrust augmentation ratio versus water/methanol flowrate at constant reheat temperature of 2847 °F

8.8 Test Summary

Total Engine Run time	2 hours, 4 minutes
Total Starts	64
Time at or above 1650°F turbine-exit temperature.	7 minutes
Estimated time at or above 100,000 rpm.	1 hour, 36 minutes

9.0 DATA REDUCTION AND TEST RESULTS

Hand calculations were done to correct performance to sea level standard day conditions. Two correction calculations were performed. One was a standard delta correction from the field altitude of 1107 feet MSL. The other was an estimated change in augmentation ratio with inlet temperature based upon data in Reference 4.

9.1 Baseline Engine Performance

Measured and corrected performance for the three baseline engine runs is as follows. A delta correction factor based on a field elevation of 1107 feet was used to calculate corrected thrust.

TABLE I

Run	*Measured Thrust (lbf)*	*Corrected Thrust (lbf)*	*Engine-inlet Temperature*	*Turbine-exit Temperature*
1	90.0	93.5	512 °R	2060 °R
2	95.2	99.0	520 °R	2088 °R
3	94.4	97.8	518 °R	2114 °R

Performance values from run two were used to calculate augmentation ratio.

9.2 Augmented Engine Performance

Engine performance with full augmentation (reheat and water/methanol injection) is presented below. Of the numerous attempts to maximize augmentation ratio, data from runs 5, 10 and 12 are most complete. The most successful augmenter configuration employed water/methanol injection upstream of the engine inlet and directly upstream of the compressor deswirl vanes. The predicted augmentation ratio of 1.33 with reheat only was achieved.

Maximum thrust measured with reheat and water/methanol augmentation was 150 lbs. This was achieved at an ambient temperature of 54° F, a reheat temperature of 2650° F and a water/methanol flow rate of 4.5 lbs per minute. Combustor flameout prevented testing at the desired water/methanol flow rate. Correcting to sea-level pressure and adjusting for improved water/methanol performance at 59°F ambient temperature yields a thrust of 157.7 lbf and an augmentation ratio of 1.586. The desired reheat temperature of 3200°F could not be achieved

with water/methanol injection. On test run 12a, which was conducted with reheat only, a temperature of 3000°F was recorded. It is believed that this value is low because recorded thrust corresponded more closely to that calculated for 3200°F. Lack of a suitable standard at this temperature precluded calibration. Figure 10 shows calculated and measured engine performance with reheat.

TABLE II

Run	*Measured Thrust (lbf)*	*Corrected Thrust (lbf)*	*Engine-inlet Temperature*	*Turbine-exit Temperature*	*Reheat Temperature*	*Water/Meth Flow (GPM)*
5	150.0	155.3	520 °R	2090 °R	3110 °R	4.5
5	147.0	152.2	520 °R	2080 °R	3260 °R	5.2
10	145.0	150.1	520 °R	2110 °R	3360 °R	4.8
12	133.0	137.9	538 °R	2116 °R	3205 °R	6.2

Test run 12c was run with water/methanol injection only and the calibration nozzle. The original intention was to obtain augmentation ratio at 100,000 rpm for various water/methanol flow rates. Because turbine overtemperature problems were experienced at 100,000 rpm with the nozzle installed, it was decided to plot maximum achievable augmentation ratio at several engine speeds. For each test point, engine speed was set and water/methanol introduced into the engine inlet and compressor exit until peak thrust was obtained. Data was then recorded. It should be noted that the data point at 93,000 rpm may not be accurate because water/methanol flow introduction was halted due to high turbine exit temperature before peak thrust was noted. Engine performance with water/methanol injection only is presented in Figure 12 below. The data point taken at 93,000 rpm has been highlighted. It should also be noted that augmentation ratio achieved may not be representative of that achievable at the engine design point where improvements in compressor performance will be less.

Initial calculations made prior to testing indicated that an augmentation ratio of 2.0 would be possible. Review of test data indicate that this goal was not reached for the following reasons:

- Compressor performance did not improve as much as predicted when water/methanol was added. Maximum measured compressor pressure ratio was 5.13 rather than the predicted 5.77.

- Maximum required reheat temperature of 3200°F was not achievable at high water/methanol flow rates. Temperature at station 7.0 when 150 lbf. thrust was achieved was only 2650°F.

- The required water/methanol flow rate was not reached due to combustor flame out problems.

9.3 Hardware Durability

The water-cooled afterburner performed admirably until damaged during test run 4. The engine experienced a flameout at 138 lbs thrust. Inspection at shutdown revealed a large bulge in the inner liner due to excess pressure in the coolant passage. It was later discovered that coolant flow rate was inadvertently set at to low a value to prevent vaporization in the manifold. Once vaporization occurred, film cooling of the inner liner was lost and it overheated and bulged inward. Figure 13 shows the damaged liner, the afterburner diffuser and the ablative coated replacement liner.

The ablative liners demonstrated lifetimes adequate for the intended mission. The Dow Corning 93-104 silicone material lasted approximately 10 minutes before large pieces began detaching from the liner and exiting the nozzle. It was found that successful operation with the silicone material was dependent upon proper priming of the metal substrate. On test run 6, a large area of silicone eroded quickly down to the base metal. Post test inspection revealed that it had delaminated from the base metal due to poor surface preparation. Once delaminated, it quickly eroded away.

The Super 32 alumina-based furnace cement performed well as a combustor liner. When properly applied, it remained intact throughout afterburner testing. It also performed well as a nozzle material although prolonged running at high reheat temperatures caused material on the inlet radius to melt and redeposit at the exit throat reducing area and nozzle efficiency.

Prolonged running at high reheat temperatures eroded the graphite nozzle. It is not known if the erosion was due to oxidation or to particle bombardment. However, the condition was duplicated on the bench using an oxygen/acetylene torch set with an oxidizing flame. After 5 minutes run time at reheat temperatures on test run 2, the graphite nozzle throat (exit) area was measured and found to be 7 % larger than the pretest value. Figure 14 shows the initial graphite nozzle configuration after test run 2. Erosion at the exit is readily apparent. Additional erosion can be seen on the outside near the exit as indicated by the darkened band. The coated-graphite nozzle fared much better during bench and engine testing lasting 5 minutes on test run 5 before the coating melted and redeposited itself at the throat leaving a rough globular texture. (See Figure 15.)

Small breaks or voids in the refractory coating resulted in recirculation areas that transferred heat quickly to the afterburner base metal. In an extreme case, a radial gap in the refractory coating where the combustor joins the exit nozzle resulted in overheat and destruction of the nozzle retainer plate after 7 minutes operation on run 10. Figure 16 is a photograph of the damaged retainer and flange. In it, areas of leakage can be seen between the bolt holes.

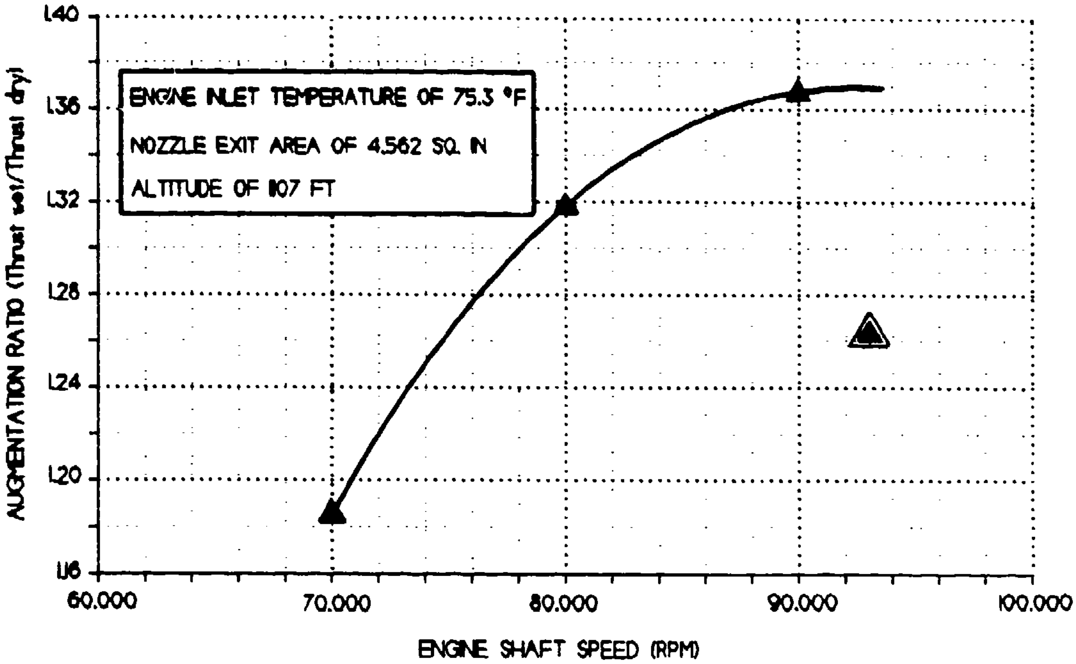


Figure 12 - Augmentation ratio versus engine shaft speed

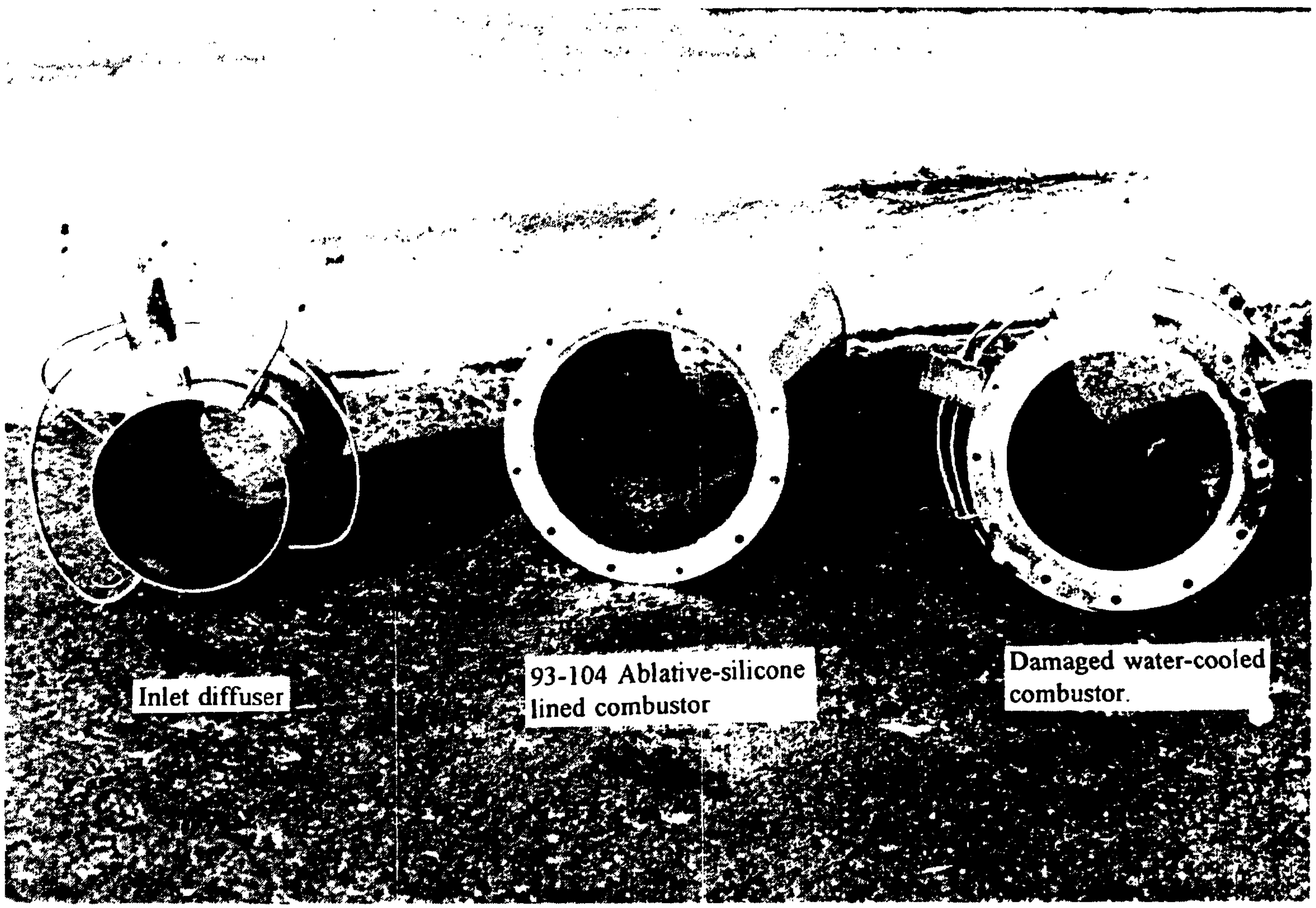


Figure 13 - Afterburner components

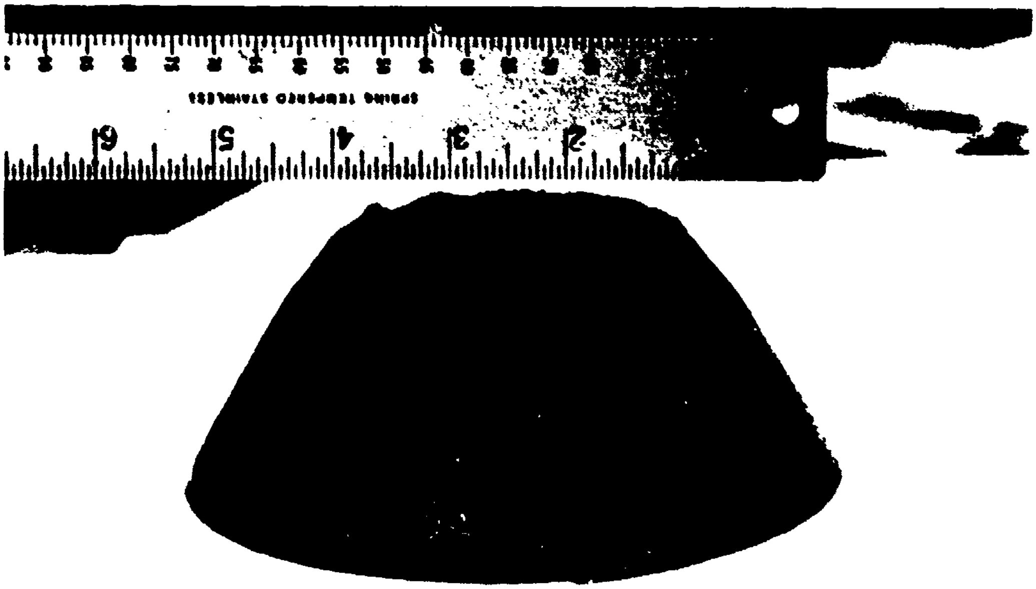


Figure 14 - Initial graphite nozzle condition after test run 2.

Figure 15 - Coated graphite nozzle after test run 5.

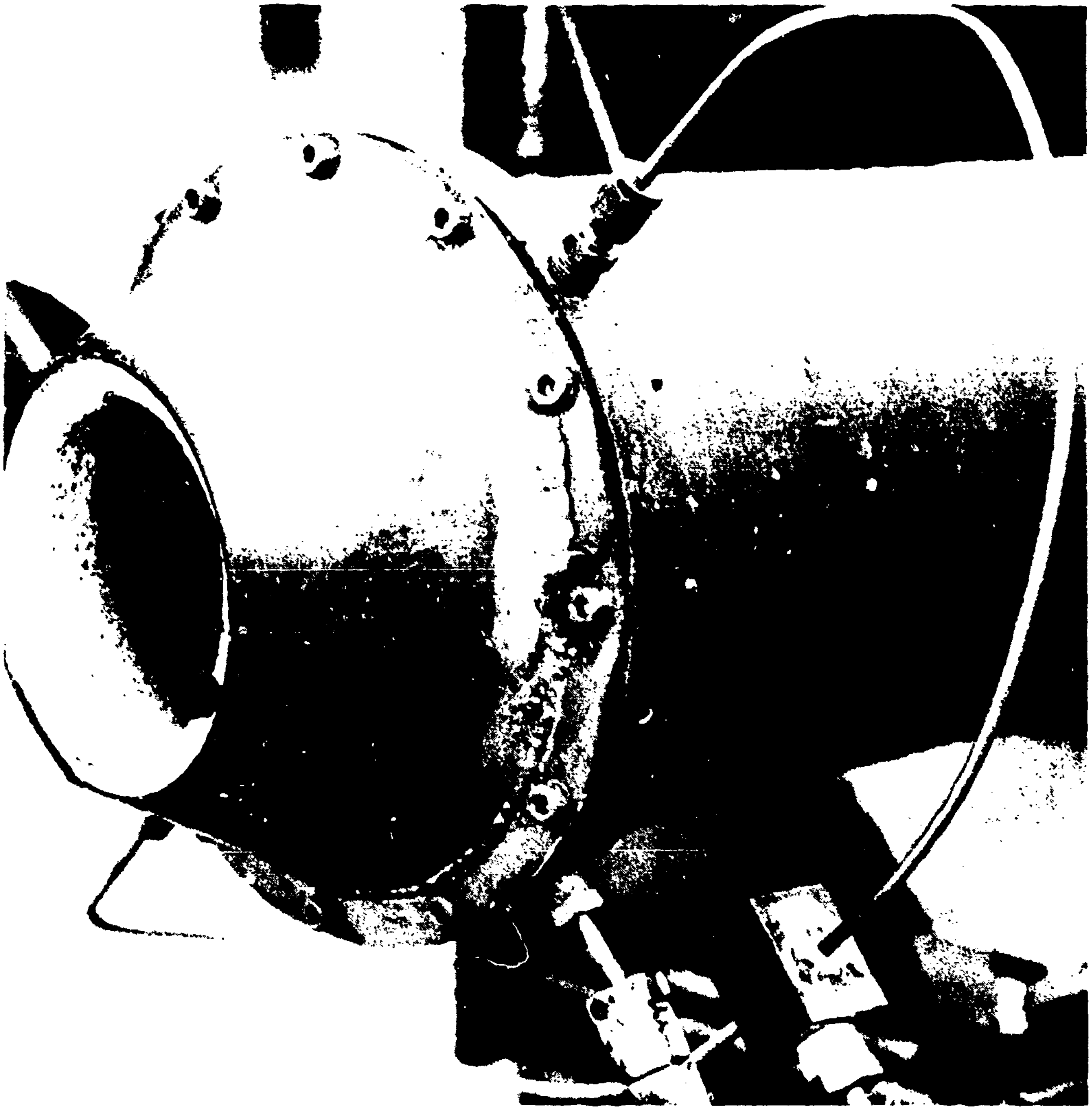


Figure 16 - Damaged nozzle retainer and flange.

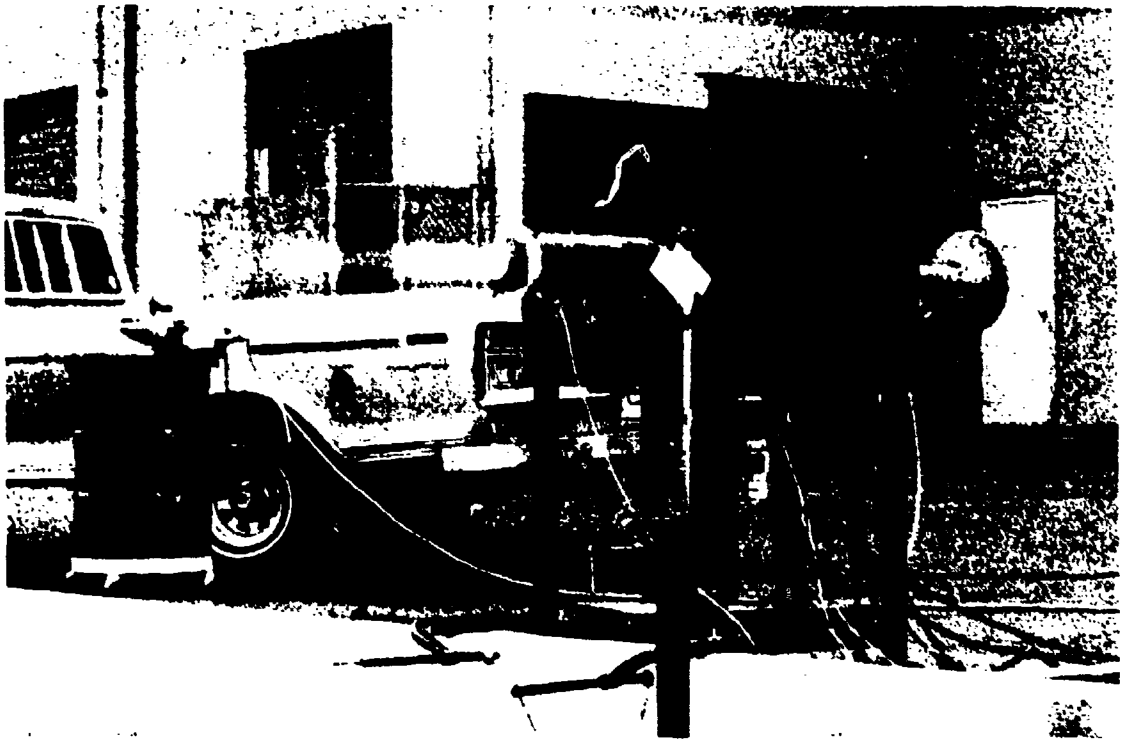


Figure 17 - Afterburner in operation.

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APPENDIX

RAW TEST DATA SHEETS

M-DOT INC.

Page No. 1 of

QUALIFICATION TEST LOG

ACCT. No. 4/CF 002	Date 2/17/93	Test Fac. M-DOT
Assembly No.	Model TJ-40	Unit Serial No.
Engineer	Technician Spencer	Supervisor
Test Type Performance (Smith)	Customer MICOM	Build No.

Start Time	Stop Time	Hours	Starts	REMARKS					
				Steady @ 65K ~ ' w/o AB					
				Steady @ 80K ~ = w/o AB					
				N	P_{1}	P_{2}	T_{2}	T_{4}	P_{4}
		w/o	A/B	65K	2" vac	14			
		with	AB	65K	1.9	15.4			
		w/o	A/B	80K	4.4	26.0			
		with	AB	80K	4.0	29.0			
				73 lbs	Thrust				
				Test #a)					

SUMMARY: Total Operating Time ______ hrs. ______ min. Ref. Data Page ______

Total Manual Starts ______

Total Automatic Starts ______ ENGINEERING ______

M-DOT INC.

Page No. 2 of

QUALIFICATION TEST LOG

ACCT. No. 61CB.002	Date 21-192	Test Fac. M-D	
Assembly No.	Model TJ-90	Unit Serial No.	
Engineer	Technician Greiner	Supervisor	
Test Type PERFORMANCE [illegible]	Customer MICOM	Build No.	

Start Time	Stop Time	Hours	Starts	REMARKS					
				$T_{AMBIENT}$ = 58.7°					
				N	T_1	T_2	T_5	T_7	
		w/o		84.2	56.7	53.3	780	68.3	
		w			49.9	52.6	961.3	2339	2314
		w/o		88.2	47.9	52.1	821.5	744	
		w		90.4	47.7	51.4	1107	2768	
				$T_{A_{Bell}}$ = 89.6					
				$T_{E_{Avg}}$ = 65.9					
				TEST '2'					

SUMMARY: Total Operating Time ______ hrs. ______ min. Ref. Data Page ______

Total Manual Starts ______

Total Automatic Starts ______ ENGINEERING ______

M-DOT INC.

Page No. 3 of

QUALIFICATION TEST LOG

ACCT. No.	91CE002	Date	3/7/92	Test Fac.	M-Dot
Assembly No.		Model	TJ-50	Unit Serial No.	
Engineer		Technician	Shreiner	Supervisor	
Test Type	Baseline Perf.	Customer	Micom	Build No.	

Start Time	Stop Time	Hours	Starts	REMARKS					
3:57	4:02			65 80 90 100 K				T_{amb} = 55.7° =	
				w/o AB					
		T		N	P_{3m}	P_3	$\dot{W}_f$	T	T
				65K	1.9	16.5	2.6	979	51
		73.7		80K	3.8	29.1	4.7	1130	48.6
		74.5		90K	5.9	42.1	9.5	1361	46.6
		(60)		100K				600	
				Reg Temp					
				Test (a)					

SUMMARY: Total Operating Time ______ hrs. ______ min. Ref. Data Page ______

Total Manual Starts ______

Total Automatic Starts ______ ENGINEERING ______

eg. (pixels)	N	7	/S	#1	#1	#3	#5	#7	#7	#6	AB/meth
	85030	32.3	853.2	5.25	57.2	29 5	2.20	1.4		1.9	– –
325	85430	42.1	824.0	5.20	56.8	34.4	3.1	1.9	759		–/✓

11/1/93

Test Run #1

3005

N RPM	T_{lbs}	T_5 °F	P_{S1}	T_1	P_{S3}	P_{S5}	P_{S7}	T_7 °F	P_{S6}	AB / METH
START 309 HALF START										
39 8540	34.5	868	5.3	54	30	1.3	2.4	807	2.0	X X
85600	89.0	1210	5.0	57	34	6.2	7.0	2761	6.3	✓ X
102000	122	1472	8.2	53.7	51	9.6	10.8	2887	6.5	✓ X
100000	135	1444	7.9	52.3	51	10.9	17.4	2727	7.6	✓ ✓

10% UNDER

Notes:

1. ENGINE FLAMEOUT OCCURRED WHILE INCREASING FUEL W/M & AB FUEL
2. AFTER TEAR DOWN NOZZLE EXIT AREA WAS MEASURED — AN INCREASE OF 7% WAS RESULTED FROM A BURNT NOZZLE
   $A_o = 6.835\ in^2$
   $A_f = 7.316\ in^2$
3. MAX THRUST = 134 lbs
4. SEE TEST PLAN # 2

1.69

TEST RUN #2

1-16-93

				[illegible]	NO EXHAUST NOZZLE		
P_1	4.8	5.8	8.0	7.8	8.0	8.2	8.0
P_5	6.5	8.3	12.7	13.2	0.	0	
P_3	34.8	41.2	—	—	—	—	
RPM	85200	90200	100050	99400	100000		10100
THRUST	52.4	65.3	95.2	97.2 103. MAX	41	46.7	50.9
T_5	1147	1264	1628	1703	1008	980	973.
T_7	—	—					
AFT Brg	94.5	98.4	108.4	106.	57.	57.3	81
T_1	57.4	56.	54.6			57.3	
T_2	63.2	60.6	60.2			46.8	
T_3	358	399	497.			169.	
OSCILLOSCOPE	7.8 ms	6.2 ms	4.2 ms		DRY	WET	

32.5

BLEW WHILE TRYING TO ADD H_2O/METH 3)

W/M 3 PEAK 300 HZ

THRUST OFFSET .5 lb

TEST RUN #3

1-20-93

TEST Run #4

	①		A/B
N	100K	100K	100K
T	67.7 / 69.2	65.?/65.?	126../135
T_5	1185/1233	1159/1160	1675
T_7	990	774/766	2804
AP: Brg	97.7	103.5	106.
T 1	53.2	56.	54.
2	57.5	61.	
3	466	468.	
P 1	8.2	8.2	
5	4.5	4.0	
6	4.6	4.0	
7	6.5	5.6	
3	41.5	45.5	

FLAMED OUT / 138 lb max thrust

NOTES: 1. WATER VAPORIZED (boiled) IN AB which CREATED A LARGE GUAGE CONDENSE INSIDE AB.

2. AB NOZZLE EXIT AREA IS TO SMALL T_5 1678°F @ 100K RPM with AB LITE T_7 2904

3. MAX THRUST 138 lbs.

4. Flame out occurred during W/M injection @ Compressor INLET. Flow RATE UNKNOWN — GUESTIMATE 1/4 design pt (targeted F/A)

5 Improved ~~starting~~ (Combustor mod worked)

M-DOT INC. TEST RUN #5

R&D • CONSULTING • PROTOTYPING & PRODUCTION

1/25/93

	1st Run w/o AB / DRY	w AB compressor/combustor injection	2nd Run AB compressor/combustor injection	3rd Run AB, compressor/combustor injection
N_r	100K	100K	100K	48700
Thrust	59	150	147	141.5
P_3	47	≈ 50	—	47
T_5	1114	1630	1620	1657
T_7	1005	2650	2800	2611
T_1	52	—	—	—
T_2	60	—	—	—
T_3	470	—	—	550
P_1	—	—	—	—
P_5	—	—	—	— P_2 = .451 psi drop
P_6	—	—	—	—
P_7	—	—	—	—
$W_{w/m}$ compressor	—	4.5 lb/min	5.17 lb/min	≈ 4.19 lb/min
$W_{w/m}$ combustor	—	—	—	≈ 3.0 lb/min
W_f engine	2.715 lbs/min	≈ 3.2 lb/min	≈ 3.17 lb/min	3.07 lb/min
W_f AB	—	≈ 5.6 lb/min	≈ 5.07 lb/min	5.4 lb/min
	Exit Area 6.830 in²			Exit Area 7.012 in² — 2.67 % increase

3418 SOUTH 48TH STREET, SUITE 2, PHOENIX, ARIZONA 85040 • (602) 921-4128

BUILD 2 TEST RUN 6 DATE 1-27-93

	CRV	A/B IDLE ADD W/M	ADD W/M ONLY		
N	100K	100K	100K		
THRST	54	125	55 CRV 726 MAX		
P_3	42				
T_5	1173	~1400			
T_7	1037	2200			
P_5	3.8				
T_1	62				
T_2	346				
T_3	457				
P_6					
~~P_7~~					
P_2					
$N_{W/M}$ COMPRESSOR		550 (4 GPM)			
$W_{W/M}$ COMBUSTOR		690 (5.715 lbs/min)			
W_f ENGINE	720	(2.715 lbs/min)			
W_f A/B					

NOTES: TEST TO ADD W/M TO A/B INLET COMB ... 150 WHEN ... STRAY'S BLEW ... ABSORBED ... ENABLE ... TIME ... AB ... SILICONE ... DECIDED TO ... MAX TIME ...

TEST RUN 7 DATE 2/13/93

	#1	#2	#3	#4			
N	100%			100%			
RST	117, 134			50			
P_3				40			
T_5				1564			
T_7				2684			
~~P_5~~							
T_1							
T_2							
T_3							
P_6							
P_7							
P_2							
$N_{W/M}$ COMPRESSOR							
$W_{W/M}$ MOTOR							
W_f ENGINE							
W_{f} AB							

131.7# max T (lower?) ow while adding W/m directly
lb combustor
115# max T 01 overspeed S/D @ 103K
115# max
144# max T

NOTES:

TEST RUN 8 — 2/10/93

	1ST	2ND	3RD	4TH	5TH
N	100 K	99 K	101 K	100 K	92 K
THRST	139	125	104	22	124
P_3			38	37	38
T_5	1700	1600	1301	~ 1600	1620
T_7	2600	2700	2450	2500	2613
P_5					
T_1			WATER/ACETONE	WATER/ACETONE	W/M w/ AMMONIUM NITRATE
T_2	W/M INJECTION S/D Lim 1720°F	W/M INJECTION @ INLET			
T_3		FIX W/M INJECTION THEN ADD TO COMBUSTOR			
P_6	/15		INCREASE IN W/M TO COMBUSTOR WHEN ENGINE BLEW OUT		
P_7					
P_2					
$W_{w/m}$ COMPRESSOR	5.41 lbm/min	≈ 31 lbm/min	≈ 22 lbm/min	≈ 4.9 lbm/min	48 lbm/min
$W_{w/m}$ COMBUSTOR		UNKNOWN FLOW RATE	≈ 26 lbm/min		
W_f ENGINE		ENGINE BLEW OUT WHILE ADDING W/M TO COMBUSTOR			
W_f AB					

NOTES:

TEST RUN 9 DATE 2/17

N	[illegible]	[illegible]	100K		
RST	550RV / 32# max	103-5 .12 :7	140# 546WM		
P_3		55			
T_5		1400 1500	1680		
T_7		2350 2000	~2800		
P_5					
T_1					
T_2					
T_3					
P_6					
P_7					
P_2					
N_{WM} compressor			570		
$W_{W/M}$ motor					
W_f engine			370		
W_f AB			700		

H_2O only into combustor when [illegible] inlet

blew out while adding water to comb.

switched to water injection at closewirl

NOTES:

TEST RUN 10 — 2/22/93

	1st Run W/AB / W/M Injection @ Deswirl	2nd Run " "	2nd data pt. on Run 2	3rd Run Opened nozzle exit area		Sundstrand nozzle baseline run 4th Run	5th Run	6th Run
N	100 K	100 K	100 K	100	100	100 K	97.5K	98
THRST	127	145	140 MAX 140 ... SEE	30	142	98	94.4	101
P_3	55		57	55	57		50	
T_5	1551	1650	1651	1563	1656	1700	1654	1696
T_7	2560	2900	2970	2780	2946			
P_5	—							
T_1	54						53	
T_2								
T_3							473	
T_6								
T_7								
P_2								
$W_{W/M}$ Compressor		≈ 4.8 lbm/min						
$W_{W/M}$ Combustor								
W_f Engine								
W_f AB								

Engine overspeed shutdown. All data taken is with the engine in non AB mode. Could not lite AB causing operator to manipulate fuel adjustments to engine / AB. S/S 1/1 light off

W/M injection @ compressor only overtemp engine

W/M injected @ compressor inlet & combustor inlet (deswirl location)
Max T_7 = ~~3400~~ 3050°F. Burned hole through nozzle casing, thus performance went down.

Engine overtemp T_5 = 1700

Engine over temp

NOTES:

TE[illegible] 11 P: 30.08 3/9/93

Rel. Humidity = 35%

N	1005				
THRST	140				
P_3	55.5				
T_5	1A1				
T_7	2818				
T_5					
T_1					
T_2	49.1				
T_3					
T_6					
T_7					
T_2					
$W_{W/M}$ COMPRESSOR	434				
$W_{W/M}$ COMBUSTOR	145				
W_f ENGINE					
W_f AB					

NOTES:

TEST RUN 12 DATE 3/22/93

			TEST #1		
N	[illegible]	100.2	100.7	100.5	
THRST	[illegible]6	101.8	114.4	126.2	
P_3	[illegible].5	48.1	50.0	50.5	
T_5	[illegible]93	1441	1535	1690	
T_7	[illegible]591	2628	2960	3002	
P_5	[illegible]0	8.6	—	—	
T_1	75.5	75.2	75.4	74.7	
T_2	83.1	81.9	81.8	—	
T_3	503.5	509.6	517.2	—	
P_6					
P_7					
P_1	7.8" Hg vac	7.8	7.8		
$W_{w/a}$ Compressor					$P_0 = 29.92$" Hg
$W_{w/a}$ Combustor					
W_f Engine					
W_f AB					

NOTES: AB TEST 4 data pts T_7 ranges: 2200-2400 °F, 2400-2600 °F, 2600-2800 °F, 2800-3200 °F

TEST RUN 12 DATE 3/22/93

		TEST #2			
N	100600	100100	99,900	99,700	
THRST	123.2	125.8	133	97.6	
P_3	52.0	53	54	52	
T_5	1502	1533	1656	1678	
T_7	2847	2828	2745	—	
P_5	—	—	—	—	
T_1	73.5	73.8	73.9	69.4	
T_2	53.8	54.1	52.0	77.7	
T_3	471	464.4		509	
P_6					
P_7					
P_1	7.5	7.65	7.5	7.4	
$W_{W/M}$ COMPRESSOR					lbm/min
$W_{W/M}$ COMBUSTOR					lbm/min
W_f ENGINE					
W_f AB				w/o	

NOTES: w/m INJECTION / w/ SUNDSTRAND NOZZLE

TEST RUN 12 DATE 3/22/93

N	70,00	7000	80.0 | 8000	90 | 90	93
THRST	27.5	33 (39.1)	44 | 58	67 | 91.6	77 96
P_3	18	18.5% BJS	31.8%	36.7%	24.6 26.3%
T_5	1104				77/96 76/96
T_7					
P_5					
T_1	73.1				
T_2	75.3				723 48
T_3	274.3				
P_6					SHUTDOWN T_5
P_7				DRY WET	
P_d	2.45				
$W_{w/a}$ Compressor	Dry	wet	DRY		
$W_{w/a}$ Combustor					
W_f Engine		augmentation RATG			
W_f AB					

NOTES:

TEST #3

Sundstrand Nozzle